



People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research



Echahid Hamma Lakhdar University – El Oued

FACULTY OF TECHNOLOGY

Dissertation

Submitted in partial fulfillment of the requirements for the degree of

ACADEMIC MASTER

Field: Science and Technology

Program: Electrical Engineering

Specialization: Networks

Theme

**The Effect of Partial Shading on the Power
Produced by Photovoltaic (PV) Panels**

Prepared by:

Rabia Khalifa

Examination Committee:

Chairperson	Cheraief Hakima	El-Oued University
Examiner	Rehouma Youcef	El-Oued University
Supervisor	BENGHARBI Abdelkader Azzeddine	El-Oued University

Academic Year: 2025/2026

Acknowledgements

First and foremost, I would like to express my deepest gratitude to Allah Almighty for giving me the strength, patience, and guidance to complete this work.

*I would like to extend my sincere thanks and appreciation to my supervisor, Dr. **BENGHARBI Abdelkader Azzeddine**, for his valuable guidance, continuous support, constructive remarks, and encouragement throughout the preparation of this dissertation. His advice and academic supervision were of great importance in improving the quality of this work.*

I am also grateful to all the teachers of the Faculty of Technology at Echahid Hamma Lakhdar University – El Oued for the knowledge and support they provided during my academic journey.

Finally, I would like to thank everyone who contributed, directly or indirectly, to the completion of this dissertation.

Dedication

First and foremost, I would like to express my deepest gratitude to Almighty God for granting me the strength, patience, and determination to accomplish this work .despite all the challenges I encountered along the way

I dedicate this work to my beloved mother, Salha, in appreciation of all the .sacrifices she has made for me from my childhood until today

I also dedicate it to my dear father, Saad, whose continuous support, encouragement, and guidance have always helped me overcome difficulties, and .who has always been, and will remain, a true role model in my life

My sincere dedication also goes to my beloved sisters, and especially to my dear .little sister, Aya

Finally, I dedicate this work to all the members of my family, whose love and support have always been a source of strength and inspiration.

Abstract:

This study aims to analyze the effect of partial shading on the power produced by photovoltaic panels. Photovoltaic solar energy is an important clean and renewable source for electricity generation. However, the performance of PV panels is affected by several external factors such as temperature, irradiance, and shading. Therefore, this work focuses on partial shading as one of the main causes of power reduction in photovoltaic systems. First, the basic concepts of photovoltaic energy and the main components of a PV system are presented. Then, the photovoltaic cell model and its electrical characteristics are discussed. The study uses MATLAB/Simulink simulation to investigate the behavior of the PV system under shading conditions. The results show that partial shading creates multiple peaks in the power-voltage characteristic, while bypass diodes protect shaded cells but modify the I-V and P-V curves. Therefore, advanced MPPT techniques are required to track the true global maximum power point.

Keywords: Photovoltaic energy; Partial shading; Solar panels; Electrical power; MPPT; MATLAB/Simulink.

المخلص:

تهدف هذه الدراسة إلى تحليل تأثير التظليل الجزئي على القدرة المنتجة من الألواح الكهروضوئية. وتعد الطاقة الشمسية الكهروضوئية مصدرًا مهمًا ونظيفًا ومتجددًا لتوليد الكهرباء. غير أن أداء الألواح الكهروضوئية يتأثر بعدة عوامل خارجية مثل درجة الحرارة، وشدة الإشعاع الشمسي، والتظليل. لذلك يركز هذا العمل على التظليل الجزئي باعتباره أحد الأسباب الرئيسية لانخفاض القدرة المنتجة في الأنظمة الكهروضوئية. في البداية، تم عرض المفاهيم الأساسية للطاقة الكهروضوئية والمكونات الرئيسية للنظام الكهروضوئي. بعد ذلك، تم التطرق إلى نموذج الخلية الكهروضوئية وخصائصها الكهربائية. وتعتمد الدراسة على المحاكاة باستعمال برنامج الماتلاب لدراسة سلوك النظام الكهروضوئي تحت ظروف التظليل. وقد أظهرت النتائج أن التظليل الجزئي يؤدي إلى ظهور عدة قمم في منحنى القدرة-الجهد، كما بينت أن الثنائيات الالتفافية تحمي الخلايا المظلمة، لكنها تغير شكل منحنى التيار-الجهد والقدرة-الجهد. لذلك، يتطلب تتبع نقطة القدرة العظمى الحقيقية استعمال تقنيات **MPPT** متقدمة. وتؤكد الدراسة ضرورة استعمال خوارزميات **MPPT** متقدمة لضمان استخراج القدرة القصوى الحقيقية.

الكلمات المفتاحية: الطاقة الكهروضوئية؛ التظليل الجزئي؛ الألواح الشمسية؛ القدرة الكهربائية؛ **MPPT**؛ الماتلاب

Table of Contents

Acknowledgements	I
<i>Dedication</i>	II
Abstract:	III
Table of Contents	IV
List of Figures.....	VIII
List of Abbreviations.....	X
General Introduction:.....	1
<i>Chapter I State of the Art of Photovoltaic Energy</i>	
I.1. Introduction	4
I.2. Definition of Solar Photovoltaic Energy.....	4
I.3. Brief History of Solar Photovoltaic Energy	5
I.4. Photovoltaic Solar Cell	6
I.4.1. Types of photovoltaic cells	6
I.4.1.1. Monocrystalline silicon photovoltaic cell	6
I.4.1.2. Polycrystalline silicon photovoltaic cell	7
I.4.1.3. Amorphous silicon cell	7
I.4.2. Advantages and disadvantages of each cell type	8
I.4.2.1. Monocrystalline silicon photovoltaic cell	8
I.4.2.2. Polycrystalline silicon photovoltaic cell	8
I.4.2.3. Amorphous silicon cell	8
I.5. Operating modes of a photovoltaic system	8
I.5.1. Autonomous mode	8
I.5.1.1. Autonomous system with storage (battery).....	9
I.5.1.2. Autonomous system without storage	9
I.5.2. Grid-connected mode	10
I.5.3. Mode connected to a generator set.....	11
I.5.4. Hybrid mode.....	11
I.6. Solar radiation	12
I.6.1. Direct radiation.....	12

I.6.2. Diffuse radiation.....	12
I.6.3. Albedo	12
I.7. Components of a photovoltaic system	13
I.7.1. Photovoltaic modules	13
I.7.2. Characteristics of a PV module	14
I.7.2.1. Open-circuit voltage	14
I.7.2.2. Short-circuit current	14
I.7.2.3. Maximum power	14
I.7.2.4. Efficiency	14
I.7.2.5. Fill factor	14
I.8. Advantages and disadvantages of photovoltaic solar energy.....	15
I.9. Conclusion.....	15

Chapter II Modelling of a Photovoltaic System

II.1 Introduction.....	17
II.2 Photovoltaic Cells	17
II.2.1 Operating Principle of a Photovoltaic Cell	18
II.2.2 Silicon as the Basic Material	18
II.2.3 Different Types of Photovoltaic Cells	20
II.3 Mathematical Models of a Solar Cell	20
II.3.1 Single-Diode Model.....	21
II.3.2 Double-Diode Model	22
II.3.3 P-V and I-V Characteristics of Photovoltaic Modules at 1000 W/m ² and 25°C	23
II.4. Grid-Connected Solar PV Systems: Parallel and Series Configurations	24
II.4.1. Series Connection of Photovoltaic Cells	24
II.4.2. Parallel Connection of Photovoltaic Cells	24
II.5 Influence of Meteorological Parameters on the Operation of the PV Generator.....	25
II.5.1 Influence of Temperature on the Cell	25
II.5.1.1 I-V Characteristic.....	26
II.5.1.2 P-V Characteristic.....	26
II.5.2 Influence of Irradiance on the Cell	27
II.5.2.1 I-V Characteristic.....	27
II.5.2.2 P(V) Characteristic	27

II.6 Shading	28
II.6.1 Definition of Shading.....	28
II.6.2 Shading Phenomenon on Photovoltaic Modules	28
II.6.3 Solutions to Limit the Impact of Shadows on Photovoltaic Panels.....	30
II.7. Conclusion	33

Chapter III Study of the adaptation stage

III.1 Introduction	35
III.2 Principle of Maximum Power Point Tracking (MPPT)	35
III.3 MPPT Management.....	36
III.4 MPPT Control	37
III.4.1 Principle of MPPT Control.....	37
III.5 Classification of Maximum Power Point Tracking Algorithms	38
III.5.1 Indirect Methods.....	38
III.5.1.1 Open-Circuit Voltage Method of the PV Generator.....	38
III.5.1.2 Short-Circuit Current Method	39
III.5.2 Direct Methods	39
III.5.2.1 Perturbation and Observation (P&O) Method.....	39
III.5.2.2 Incremental Conductance Method.....	41
III.5.2.3 Classical MPPT Control	43
III.6 DC-DC Converter (Chopper)	43
III.6.1 Converter Types	44
III.6.1.1 Step-Down Chopper, or Buck Converter	44
III.6.1.2 Step-Up Chopper, or Boost Converter	44
III.6.1.3 Buck-Boost Converter	45
III.7 Equivalent Mathematical Model	46
III.8 Conclusion.....	47

Chapter IV Simulation and results discussion

IV.1 Introduction	49
IV.2 Simulation Environment	49
IV.2.1 Characteristics of the photovoltaic module	50
IV.3 I-V Characteristics Under Partial Shading Conditions	52
IV.4 P-V Characteristics Under Partial Shading Conditions.....	54

IV.5 Effect of Bypass Diodes Under Partial Shading	55
IV.6 Comparison Between PV Current and Bypass Diode Current.....	56
IV.7 Conclusion.....	57
General Conclusion:	59
Bibliography:	62

List of Figures

Figure (I.1): Solar source illustration.	4
Figure (I.3): Types of solar cells.	6
Figure (I.4): Monocrystalline cells.	6
Figure (I.5): Polycrystalline cells.	7
Figure (I.6): Amorphous photovoltaic cell.	7
Figure (I.7): General layout of an autonomous photovoltaic system.	9
Figure (I.8): Autonomous system with storage (battery).	9
Figure (I.9): Autonomous system without storage.	10
Figure (I.10): Grid-connected photovoltaic system.	10
Figure (I.11): Photovoltaic system connected to a generator set.	11
Figure (I.12): Hybrid autonomous photovoltaic supply system.	12
Figure (I.13): Schematic view of the different types of radiation.	13
Figure (I.14): Structure of a photovoltaic module.	13
Figure (II.1): Solar cells.	17
Figure (II.2): Operating principle of a photovoltaic cell.	18
Figure (II.3): Silicon photovoltaic cells.	19
Figure (II.4): Equivalent electrical circuit of a solar cell.	21
Figure (II.5): Equivalent electrical circuit of a solar cell (double-diode model).	22
Figure (II.5): I-V characteristic of photovoltaic modules at 1000 W/m ² and 25°C.	23
Figure (II.6): P-V characteristic of photovoltaic modules at 1000 W/m ² and 25°C.	23
Figure (II.7): I-V characteristic of two photovoltaic cells connected in series.	24
Figure (II.8): I-V characteristic of two photovoltaic cells connected in parallel.	25
Figure (II.7): I(V) characteristic for different temperatures (G = 1000 W/m ²).	26
Figure (II.8): P(V) characteristic for different temperatures (G = 1000 W/m ²).	26
Figure (II.9): I(V) characteristic for different irradiance levels (T = 25°C).	27
Figure (II.10): P(V) characteristic for different irradiance levels (T = 25°C).	28
Figure (II.11): I-V characteristic of a PV cell.	29
Figure (II.12): Characteristics of PV cells for a given current in the presence of shading.	30
Figure (II.13): Some types of panels.	31
Figure (II.14): Microinverter installation diagram.	31
Figure (II.15): IQ7 microinverter.	32

Figure (II.16): Inclination of solar panels.....	32
Figure (III.1): Principle diagram of the MPPT converter.....	35
Figure (III.2): Search and recovery of the maximum power point.....	36
Figure (III.3): I-V curves and output power curve for a photovoltaic module.....	37
Figure (III.4): Convergence scheme toward the MPP using P&O.	40
Figure (III.5): Typical flowchart of the P&O method.	41
Figure (III.6): Flowchart of the incremental conductance method.....	42
Figure (III.7): Functional diagram of the classical MPPT control.	43
Figure (III.8): Step-down chopper, or Buck converter.....	44
Figure (III.9): Step-up chopper, or Boost converter.....	45
Figure (III.10): Buck-Boost converter.....	45
Figure (III.12): Equivalent diagram of the boost converter when $t \in [0, \alpha T_s]$	46
Figure (IV.1) : Electrical parameters of the photovoltaic module used in the simulation	50
Figure (IV.2) : Partial shading scenario applied to the PV array	51
Figure (IV.3) : I-V characteristics for three different partial shading patterns.....	52
Figure(IV.4) : Power-Voltage (P-V) characteristics under partial shading conditions	53
Figure (IV.5) : Comparison of PV string current and bypass diode current under partial shading.....	55
Figure(IV.6) : Activation of bypass diodes at specific voltage levels under partial shading	56

List of Abbreviations

PV: Photovoltaic
PVG: Photovoltaic Generator
STC: Standard Test Conditions
DC: Direct Current
AC: Alternating Current
MPPT: Maximum Power Point Tracking
MPP: Maximum Power Point
GMPP: Global Maximum Power Point
LMPP: Local Maximum Power Point
P&O: Perturb and Observe
IncCond: Incremental Conductance
PSO: Particle Swarm Optimization
I-V: Current-Voltage Characteristic
P-V: Power-Voltage Characteristic
Voc: Open-Circuit Voltage
Isc: Short-Circuit Current
Pmax: Maximum Power
Wp: Watt-Peak
Rs: Series Resistance
Rsh: Shunt Resistance
Iph: Photocurrent
MATLAB: Matrix Laboratory
Simulink: Simulation and Model-Based Design Environment

General Introduction

General Introduction

The increasing global demand for electrical energy, together with the environmental problems caused by fossil fuels, has encouraged the development of renewable energy sources. Among these sources, solar photovoltaic energy has become one of the most promising solutions because it converts sunlight directly into electricity, offers clean energy production, and can be used in both isolated and grid-connected systems.

Photovoltaic panels are widely used in domestic, industrial, and remote-area applications. However, their performance depends strongly on external operating conditions, especially solar irradiance, temperature, and shading. Under ideal conditions, a photovoltaic module produces its maximum power when all cells receive uniform solar radiation. In real installations, this condition is not always achieved. Buildings, trees, clouds, dust, chimneys, and other obstacles may partially shade the photovoltaic surface, causing non-uniform irradiance across the cells or modules. [1]

Partial shading is one of the most serious problems affecting photovoltaic systems. Since photovoltaic cells are generally connected in series, the shaded cell or group of cells can limit the current of the entire string. This leads to a reduction in the produced power, the activation of bypass diodes, and the appearance of several local maximum power points on the power-voltage curve. As a result, conventional maximum power point tracking algorithms may fail to locate the true global maximum power point, which causes additional energy losses. [1]

The main objective of this work is to study the effect of partial shading on the power produced by photovoltaic panels. To achieve this objective, the dissertation first presents the general principles of photovoltaic energy, including the history, types of solar cells, operating modes, solar radiation, and components of photovoltaic systems. It then focuses on the electrical modelling of the photovoltaic cell and the influence of meteorological parameters such as temperature and irradiance. After that, the principle of maximum power point tracking and DC-DC converters is introduced. Finally, a simulation study is carried out in order to analyze the behavior of photovoltaic panels under uniform and partially shaded conditions.

This dissertation is organized into four chapters. The first chapter presents the state of the art of photovoltaic energy. The second chapter deals with the modelling of the photovoltaic cell and the influence of temperature and irradiance on its electrical characteristics. The third chapter

introduces maximum power point tracking techniques and DC-DC converters. The fourth chapter is devoted to simulation and analysis of partial shading effects on photovoltaic power production.

Chapter I

State of the Art of Photovoltaic Energy

I.1. Introduction

Solar energy is an energy source that depends on the sun. This energy makes it possible to generate electricity by means of photovoltaic panels or solar thermal and photovoltaic power plants.

Energy sources indirectly derived from solar energy include hydropower, which comes from the kinetic energy of water whose cycle depends on the thermal energy of the sun; wind energy, which comes from the kinetic energy of wind, itself linked to solar heating, evaporation of water, the Earth's rotation and the Coriolis force; marine and wave energy related to the movement of oceans and rivers; biomass and wood energy; and very low-temperature geothermal energy resulting from surface soil layers heated by the sun. [1]

Solar energy is therefore one of the main forms of renewable energy. Over longer time scales, fossil fuels may also be considered indirectly linked to solar energy because they originate from organic matter created through photosynthesis, such as coal, oil and natural gas.



Figure (I.1): Solar source illustration. [1]

I.2. Definition of Solar Photovoltaic Energy

The use of electricity generated by photovoltaic panels is not limited to buildings. Since surplus production can be sent to the public grid, this energy may be consumed by any electrical device. The global interest in solar photovoltaic energy continues to grow steadily. [2]

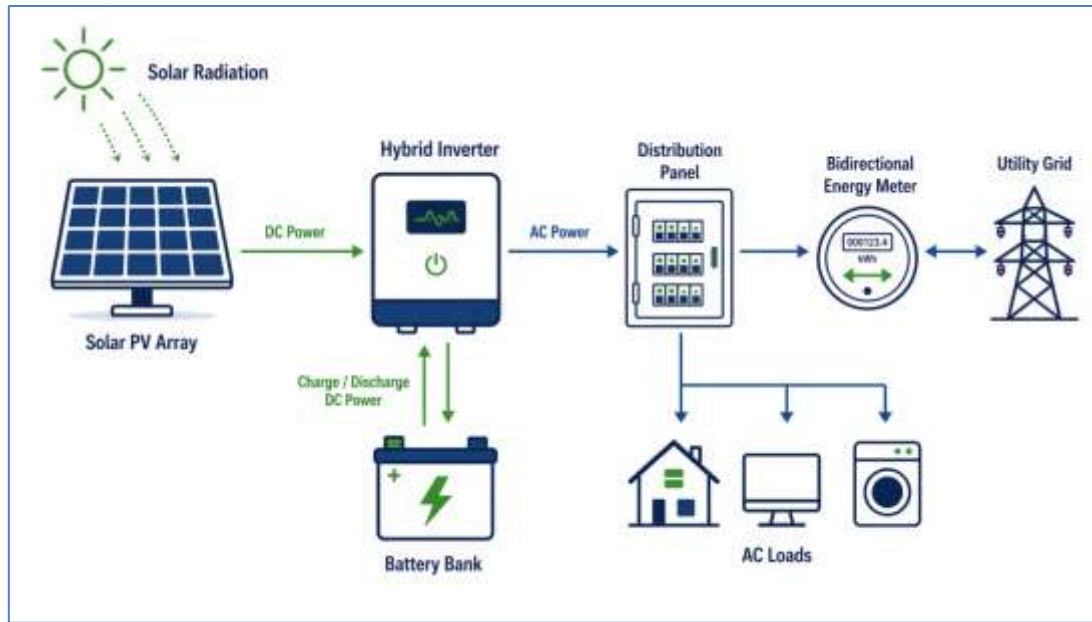


Figure (I.2): Photovoltaic system.

I.3. Brief History of Solar Photovoltaic Energy

In 1838, photovoltaic solar energy entered the history of energy when the French scientist Alexandre Edmond Becquerel discovered the photovoltaic effect for the first time. While experimenting with an electrolytic battery equipped with platinum electrodes, he observed that the electric current increased when the system was exposed to sunlight. This marked the starting point of photovoltaic energy. [2]

Another important step was made in 1873 when the English electrical engineer Willoughby Smith identified the photovoltaic effect in solids, especially selenium. A few years later, in 1877, William Grylls Adams and his student Richard Evans Day showed that selenium could produce electricity when exposed to light, thereby creating the first selenium photovoltaic cell.

In 1953, Calvin Fuller, Gerald Pearson and Daryl Chapin developed the silicon solar cell. This cell generated enough electricity and offered sufficient efficiency to power small electrical devices. Commercial solar cells appeared in 1956, although their cost remained very high until around 1970, when the price of solar cells dropped considerably. Since the late 1950s, solar cells have also been used in American and Soviet satellites. [2]

I.4. Photovoltaic Solar Cell

I.4.1. Types of photovoltaic cells

Crystalline silicon solar cells are the most widespread. They are generally manufactured in round, square or pseudo-square wafer shapes. They are called crystalline because silicon has the properties of a crystal, with an ordered atomic arrangement. [3]

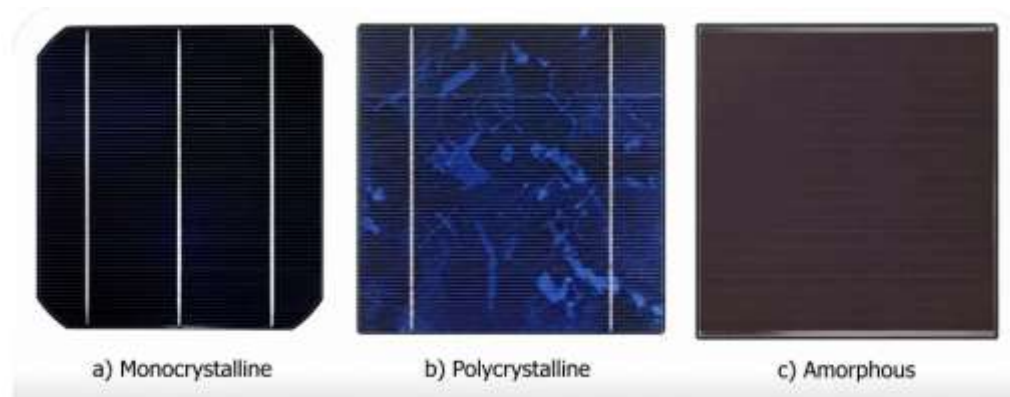


Figure (I.3): Types of solar cells.

I.4.1.1. Monocrystalline silicon photovoltaic cell

This type of photovoltaic cell is one of the most widely used. It is made from monocrystalline silicon cut into a single wafer. It is used to compose solar panels that produce electricity for houses or for the public grid. Monocrystalline silicon is obtained by cooling molten silicon until it becomes a uniform crystal, which is then sliced into thin wafers. Its color is generally dark blue and homogeneous, without visible crystal traces. [3]

Monocrystalline cells

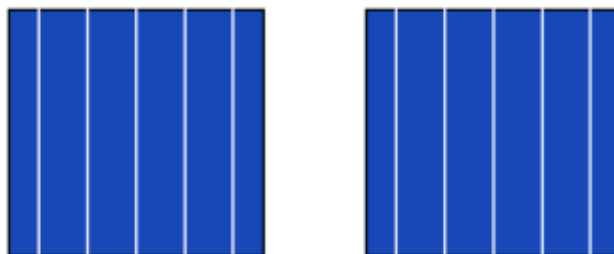


Figure (I.4): Monocrystalline cells.

I.4.1.2. Polycrystalline silicon photovoltaic cell

This photovoltaic cell is easily recognized by its blue crystal appearance. It is generally square in shape and is commonly used in domestic, agricultural and industrial installations. Polycrystalline silicon is obtained by melting silicon in a square metallic mold called an ingot mold. Its surface is marked by visible crystal patterns, which make this technology easy to identify. [2]



Figure (I.5): Polycrystalline cells.

I.4.1.3. Amorphous silicon cell

The amorphous silicon photovoltaic cell consists of a thin silicon layer, much thinner than monocrystalline or polycrystalline cells. It is mainly used in low-power devices such as solar watches, garden lighting and solar calculators. Amorphous silicon is obtained from silicon gas deposited onto a support made of glass, flexible plastic or metal by means of vacuum deposition. These cells are usually dark gray. [3]

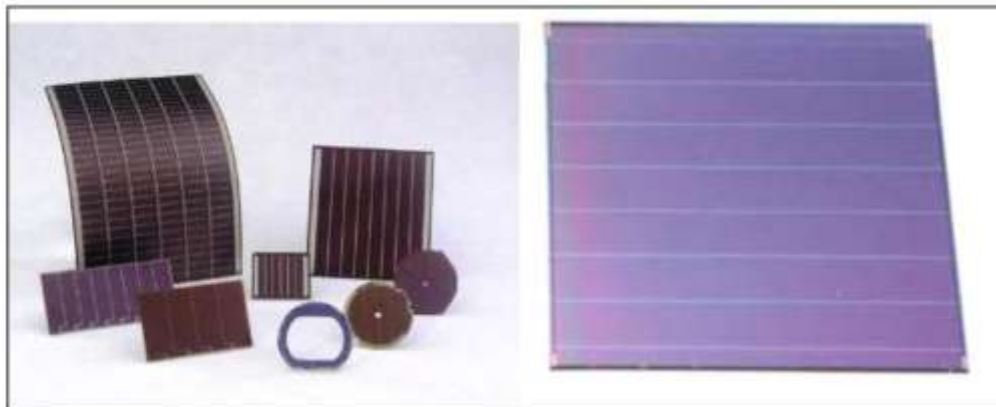


Figure (I.6): Amorphous photovoltaic cell.

I.4.2. Advantages and disadvantages of each cell type

I.4.2.1. Monocrystalline silicon photovoltaic cell

This type of cell offers one of the best efficiencies on the market, close to 25%. The service life of solar panels made of monocrystalline silicon can reach around 30 years, which makes them very profitable despite their high initial cost. Their main drawback is the drop in performance when solar radiation is insufficient; therefore, they are more suitable for highly sunny regions. [2]

I.4.2.2. Polycrystalline silicon photovoltaic cell

The manufacturing process of this technology is simpler than that of monocrystalline silicon, which reduces its cost. Its efficiency is generally between 10% and 15%, lower than that of monocrystalline cells. However, it has the advantage of operating relatively well under cloudy weather due to its irradiation flexibility. [3]

I.4.2.3. Amorphous silicon cell

This solar cell presents several advantages. It is inexpensive to manufacture and may be integrated on different rigid or flexible supports. Another positive point is its ability to capture solar rays even in cloudy conditions. Its main disadvantage is its low efficiency, which is around 7% at most, meaning that a larger panel surface is needed to obtain useful output. Its performance also decreases over time. [2]

I.5. Operating modes of a photovoltaic system

Three main modes of operation are generally distinguished for a photovoltaic panel: autonomous mode, grid-connected mode and hybrid mode. [3]

I.5.1. Autonomous mode

In autonomous mode, the photovoltaic generator is the only electrical energy source used to supply receivers such as houses, cottages or camps in remote regions, as well as applications such as monitoring and water pumping. In this configuration, the PV field charges the battery during sunshine periods, the battery supplies the load and stores electrical energy, the charge controller protects the battery against overcharge and deep discharge, and a converter makes it possible to use either direct current or alternating current equipment.

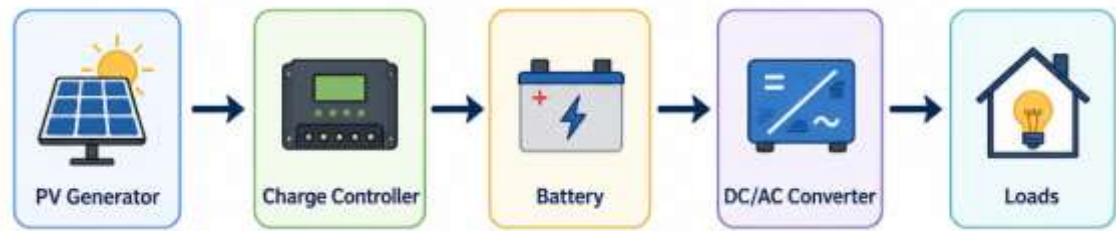


Figure (I.7): General layout of an autonomous photovoltaic system.

I.5.1.1. Autonomous system with storage (battery)

This is the most common photovoltaic system. The PV field acts as a charger for the battery, and the electricity can then be used at any time. This solution is particularly suitable for domestic lighting, since electricity is also needed when there is no daylight. [3]

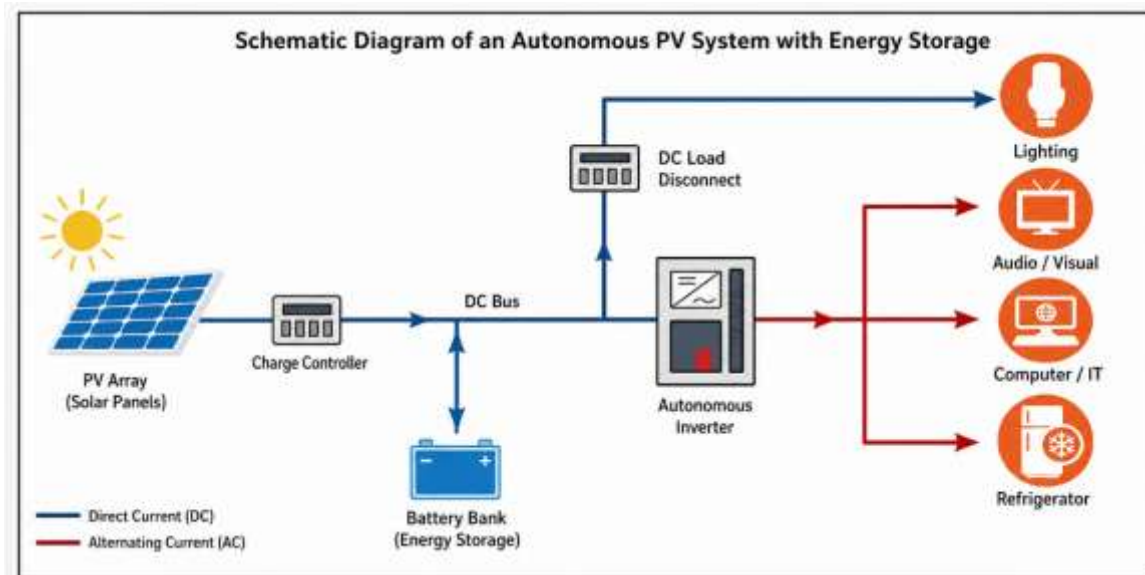


Figure (I.8): Autonomous system with storage (battery).

I.5.1.2. Autonomous system without storage

This type of system does not require electricity storage, either because the energy produced by the cells is sufficient under low illumination, as in the case of calculators, or because the operating time of the load is not critical, as for water pumping systems. [3]

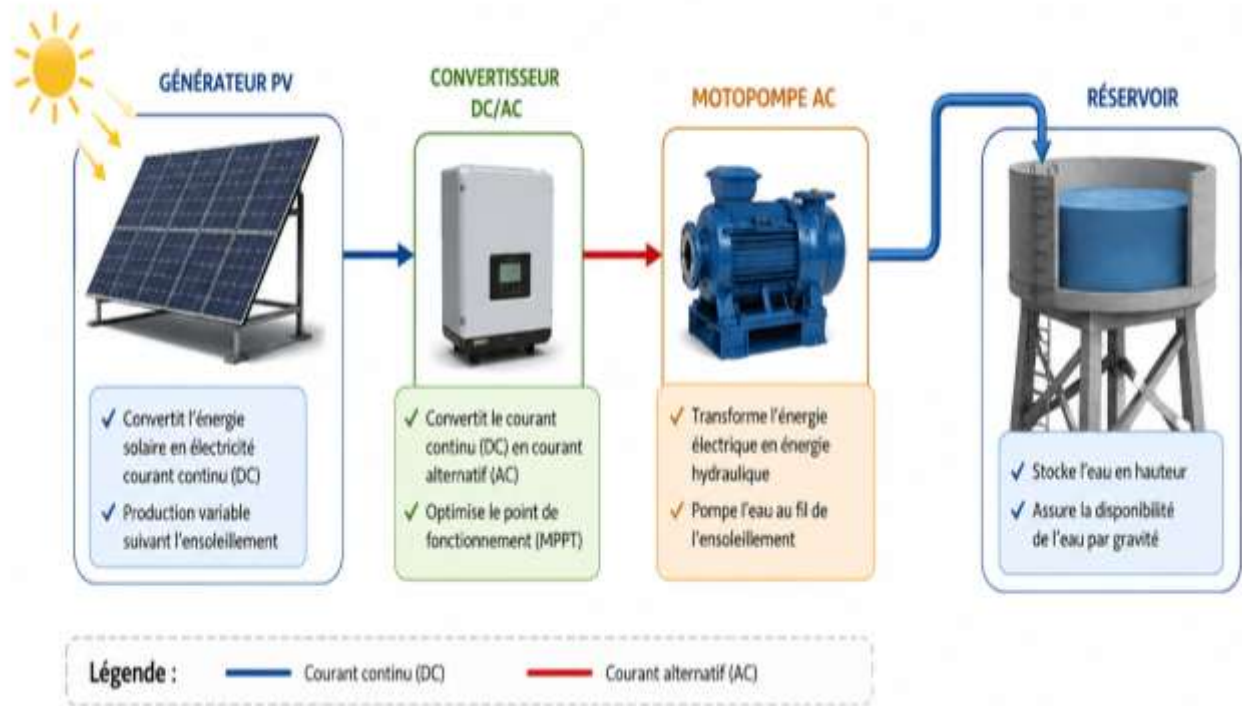


Figure (I.9): Autonomous system without storage.

I.5.2. Grid-connected mode

In this mode, the photovoltaic system is connected directly to the electrical grid and is installed close to the demand. It may be mounted on an individual residence or a commercial center so that it feeds the local load and injects surplus daytime production into the grid. At night, the load draws the required energy from the grid. This solution avoids the cost of electricity storage and reduces the need for batteries, which lowers the overall system cost. [4]

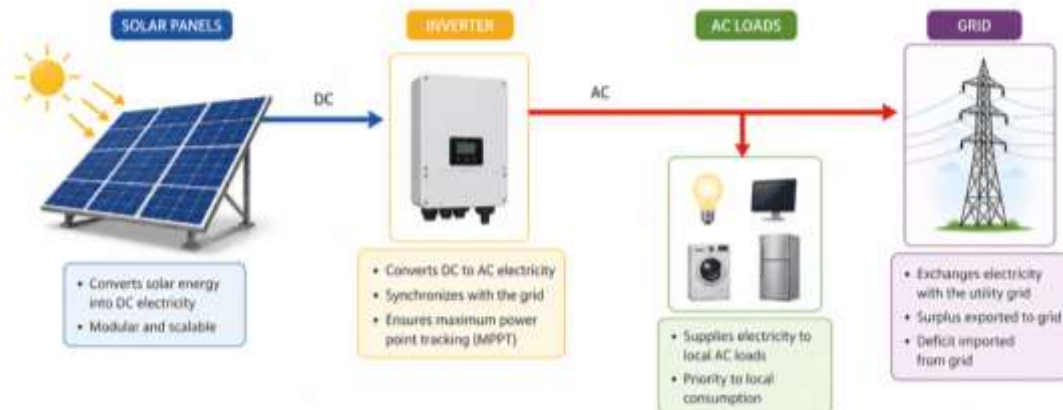


Figure (I.10): Grid-connected photovoltaic system.

I.5.3. Mode connected to a generator set

This system is mainly used in remote communities or villages. The PV generator operates in parallel with diesel generators of the village network and provides electricity when solar radiation allows it. This reduces expensive diesel fuel consumption in remote areas and decreases the operating hours of the generators. [4]

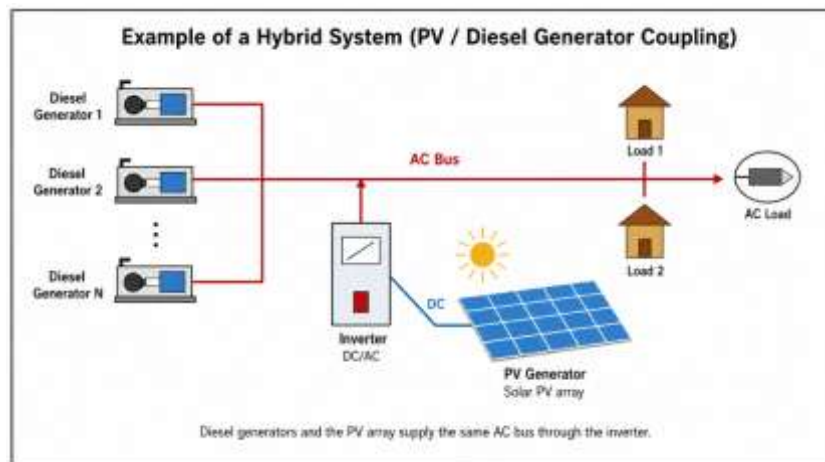


Figure (I.11): Photovoltaic system connected to a generator set.

I.5.4. Hybrid mode

A hybrid energy system includes more than one electricity source such as photovoltaic panels, fuel cells, wind generators, storage batteries and generator sets. This type of installation is often used for electrification far from the grid. Different configurations are possible, such as PV/thermal, PV/battery, PV/fuel cells, PV/wind/battery, PV/wind and PV/generator set. The choice mainly depends on the meteorological characteristics of the installation site. [3]

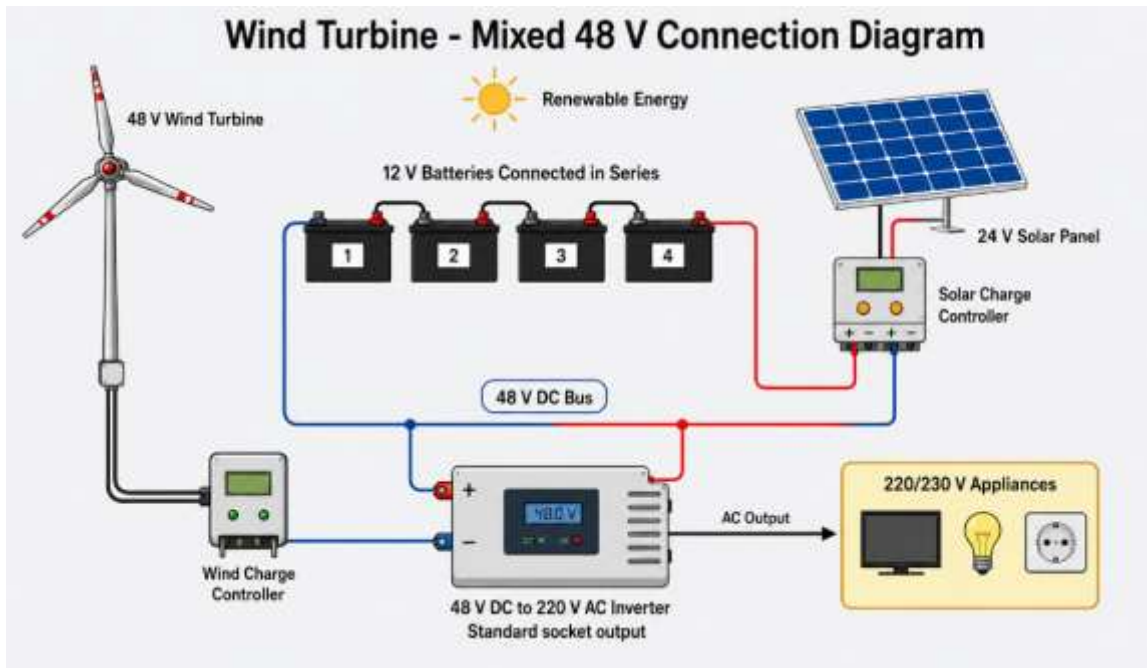


Figure (I.12): Hybrid autonomous photovoltaic supply system.

I.6. Solar radiation

Solar radiation is the raw material of solar energy. It is an electromagnetic wave propagation with wavelengths ranging approximately from 0.2 to 4×10^{-6} m. It does not need a physical medium to travel. When it reaches the ground, part of its intensity has already been lost because part of the ultraviolet radiation is absorbed in the atmosphere. Three main types of solar radiation are generally distinguished: direct radiation, diffuse radiation and albedo. [4]

I.6.1. Direct radiation

Direct radiation is the radiation received directly from the sun. It creates shadows and can be concentrated by mirrors. It may be measured by means of a pyrheliometer. [4]

I.6.2. Diffuse radiation

Diffuse radiation is emitted by obstacles such as clouds, the ground and buildings, and it reaches the receiver from all directions. It may be measured by a pyranometer equipped with a sun-shading screen. [4]

I.6.3. Albedo

Ground albedo is the radiation reflected by the ground or by objects located on its surface. This albedo can become significant when the surface is highly reflective, such as water or snow. [4]

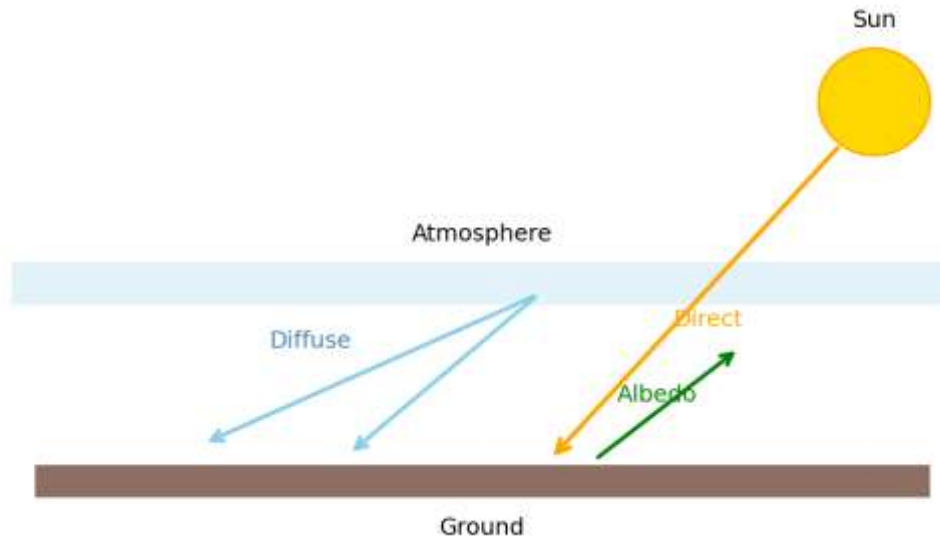


Figure (I.13): Schematic view of the different types of radiation.

I.7. Components of a photovoltaic system

I.7.1. Photovoltaic modules

A photovoltaic module is a direct current electrical generator when exposed to light. It generally consists of a rigid frame, often made of aluminum, which allows fixing, and a transparent tempered glass cover on the upper side. Inside, several photovoltaic cells are electrically connected together. These cells generate the current. They are assembled in series or in parallel inside the module in order to increase power and improve resistance to the external environment. [5]

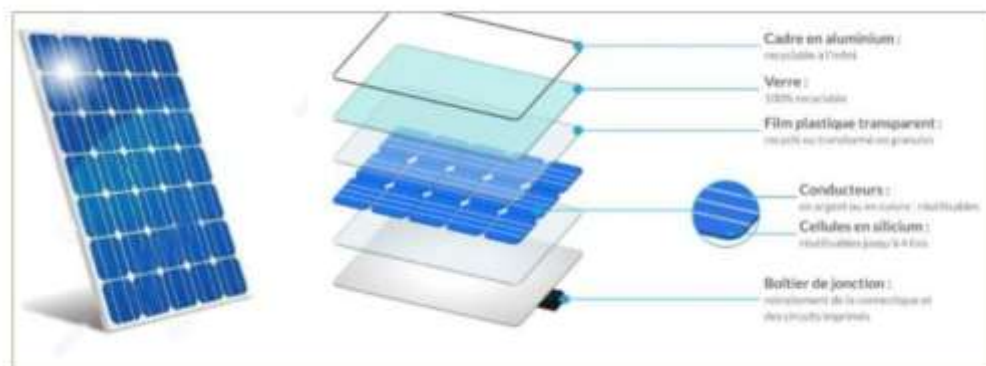


Figure (I.14): Structure of a photovoltaic module.

I.7.2. Characteristics of a PV module

I.7.2.1. Open-circuit voltage

When a photovoltaic cell is placed under a constant light source without any load connected to its terminals, it produces a continuous voltage of about 0.6 V. This voltage is called the open-circuit voltage, and it varies slightly with temperature and illumination. [5]

I.7.2.2. Short-circuit current

Conversely, if the photovoltaic cell is short-circuited, it delivers a maximum current at zero voltage. This is called the short-circuit current. The photocurrent provided by the cell is proportional to light intensity and to the panel area involved; therefore, the greater these parameters are, the larger the resulting current will be. [5]

I.7.2.3. Maximum power

The main objective for the user of a photovoltaic generator is to obtain the most optimal energy production possible. The maximum electrical power that a module can provide is associated with a maximum voltage U_{max} and a maximum current I_{max} . Under standard test conditions (25°C and an irradiance of 1000 W/m²), this maximum power is called peak power and is measured in watt-peak (Wp). [5]

$$P_{max} = V_{max} \times I_{max} \dots\dots\dots I.1$$

I.7.2.4. Efficiency

Energy efficiency is defined as the ratio between the maximum produced power and the solar radiation power reaching the module. If S is the module area and E is the irradiance in W/m², then the efficiency may be written as: [5]

$$\eta = P_m / (S \times E) \dots\dots\dots I.2$$

where η is efficiency, P_m is the peak power of the photovoltaic module, S is the module area, and E is the irradiance under STC conditions. [5]

I.7.2.5. Fill factor

For a good-quality solar cell, the fill factor is generally greater than 0.7 and decreases when temperature increases. The fill factor is a measure of the effectiveness of the real I-V characteristic of solar cells.

$$FF = (V_{max} \times I_{max}) / (V_{oc} \times I_{sc}) \dots\dots\dots I.3$$

I.8. Advantages and disadvantages of photovoltaic solar energy

Advantages:

- ✓ Independent energy source, since the fuel - solar radiation - is renewable and free.
- ✓ Clean and non-polluting energy that does not emit greenhouse gases and does not generate waste during operation.
- ✓ Produces the required electrical energy and reduces vulnerability to power failures.
- ✓ Easy system expansion; the installation size may be increased later to follow load requirements.
- ✓ Selling surplus production may help recover the investment cost or even generate income.
- ✓ Minimal maintenance and no noise during operation.

Disadvantages:

- ✓ Manufacturing photovoltaic panels requires advanced technology, extensive research and development, and costly investments.
- ✓ The efficiency of photovoltaic panels remains relatively limited.
- ✓ Domestic installations often require an auxiliary storage system such as batteries.

I.9. Conclusion

In this chapter, we reviewed the history of photovoltaic energy and followed its development from the first observations of the photovoltaic effect to the emergence of modern solar cells. We also highlighted the many advantages of this clean and renewable energy source, including its ability to generate electricity without harmful emissions, its versatility in domestic and industrial applications, and its potential to reduce dependence on fossil fuels. At the same time, we pointed out the main drawbacks associated with this technology, especially cost and efficiency limitations.

Chapter II
Modelling of a Photovoltaic System

II.1 Introduction

Photovoltaic solar energy results from the direct transformation of part of light into electricity. This conversion is carried out through a so-called photovoltaic (PV) cell, based on a physical phenomenon called the photovoltaic effect, which consists of producing an electromotive force when the cell is exposed to light. The generated voltage may vary depending on the material used to manufacture the cell. The connection of several cells in series and/or in parallel gives rise to a photovoltaic generator (PVG), whose current-voltage characteristic (I-V) is nonlinear and presents a maximum power point. Today, depending on need, the electrical energy produced is available either as direct electricity to supply a load or as energy stored in batteries. [6]

This chapter focuses on photovoltaic conversion. First, the structure and operating principle of photovoltaic cells are briefly described. The chapter then studies the influence of meteorological parameters, namely temperature and irradiance, on the electrical behavior of a solar cell. A PV model is also presented, specifically the single-exponential model.

II.2 Photovoltaic Cells

The operation of solar panels depends on one main component: the photovoltaic cell. These small square elements, which form photovoltaic modules, have the remarkable ability to convert sunlight into electricity. They are the building blocks of solar panels. They are electronic components that produce electricity from sunlight. They are very thin, approximately 200 micrometers, and only a small quantity of material is sufficient for their manufacture. Each solar panel generally contains between 60 and 72 photovoltaic cells. [6]



Figure (II.1): Solar cells.

II.2.1 Operating Principle of a Photovoltaic Cell

The operation of a photovoltaic cell is relatively simple. A semiconductor, such as silicon, with a negative side and a positive side is exposed to light. When photons strike the silicon atoms, they set electrons in motion; these electrons move in different directions according to their charge. This movement of electrons generates an electric current. In order for electrons to be attracted to one side or the other of the device, the photovoltaic cell must have a negative side and a positive side. The silicon used on the surface is therefore previously charged, or “doped,” negatively by adding phosphorus. Similarly, the silicon used on the back side of the photovoltaic cell is positively charged with boron. This charge difference between the lower side and the upper side causes electron movement, as shown in the figure below. [7]

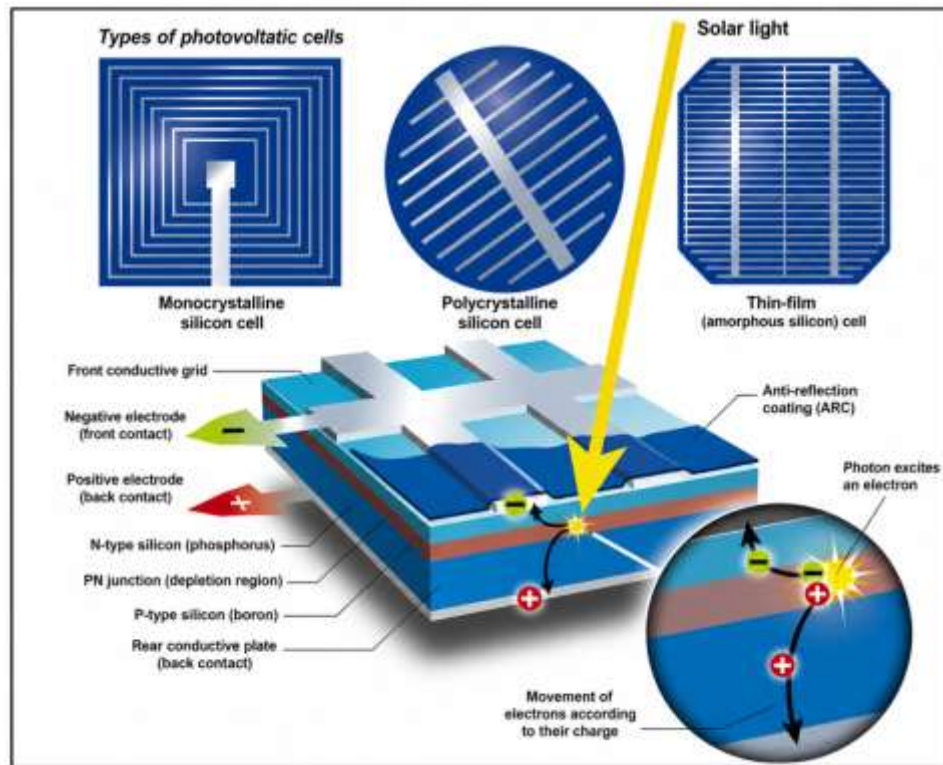


Figure (II.2): Operating principle of a photovoltaic cell.

II.2.2 Silicon as the Basic Material

The most widely used material for manufacturing photovoltaic cells is silicon, obtained from silica, which is abundantly present in sand or quartz. Produced in the form of an almost pure ingot, silicon is then cut into thin slices called wafers. These wafers are treated to obtain a positive side and a negative side in order to form photovoltaic cells. [7]

Silica is widely available and inexpensive. It is the transformation of silica into silicon, followed by wafer cutting and chemical treatment, that accounts for the high financial and environmental cost of manufacturing silicon-based photovoltaic cells. Depending on the processes used, different types of silicon can be obtained: [7]

- Amorphous silicon;
- Polycrystalline silicon;
- Monocrystalline silicon.

Recently, the use of other materials has been studied in order to respond to the rapid global growth in demand for photovoltaic panels by finding less expensive and cleaner processes. The use of copper or plastic materials, in particular, appears to offer interesting prospects; however, their efficiencies remain too low to compete seriously with silicon. [7]

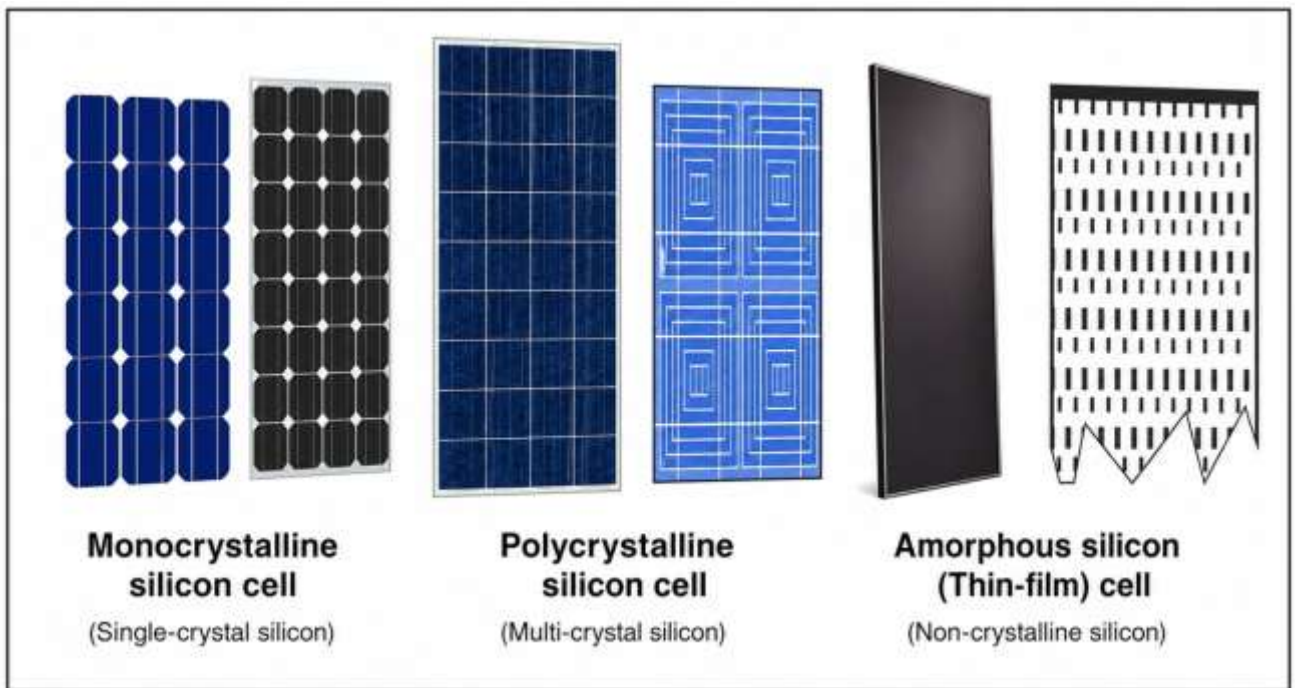


Figure (II.3): Silicon photovoltaic cells.

II.2.3 Different Types of Photovoltaic Cells

The table below summarizes the main types of photovoltaic cells, their maximum efficiencies, and their principal advantages and disadvantages. [7]

Cells	Maximum efficiency	Advantages	Disadvantages
Amorphous silicon photovoltaic cells 	8 %	• Proven and affordable technology. • Can be used in flexible or rigid form. • Works even under low light.	• Very low efficiency. • Not suitable for high-output production.
Polycrystalline silicon photovoltaic cells 	18 %	• Best efficiency/price ratio on the market.	• Costly manufacturing process. • Requires optimal light conditions.
Monocrystalline silicon photovoltaic cells 	25 %	• Excellent efficiency. • Uniform appearance often considered more aesthetic than polycrystalline silicon.	• Very costly manufacturing process. • Requires optimal light conditions.

Table (II.1): Different types of photovoltaic cells.

II.3 Mathematical Models of a Solar Cell

The simplest equivalent circuit of a solar cell is a current source connected in parallel with a diode, as shown in Figure (II.4). The output of the current source is directly proportional to the light falling on the cell. In darkness, the solar cell is inactive and behaves like a diode: it produces neither current nor voltage. However, when light falls on the solar cell, it generates a diode current. The diode D determines the I-V characteristics of the cell. A series resistance represents the internal resistance of each cell, while the shunt resistance R_{sh} is often neglected because it has a high resistance value. [9]

II.3.1 Single-Diode Model

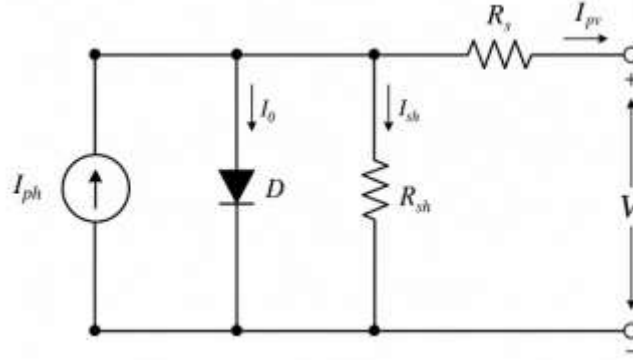


Figure (II.4): Equivalent electrical circuit of a solar cell.

The current is given by the following relation:

$$I_{pv} = I_{ph} - I_0 \left[\exp \left(\frac{q(v + I_{RS})}{n \cdot K \cdot N_s \cdot T} \right) - 1 \right] - I_{sh} \dots \dots \dots \text{II.1}$$

$$I_{ph} = [I_{cc} + Ki(T - 298)] \cdot \frac{G}{1000} \dots \dots \dots \text{II.2}$$

$$I_0 = I_{rs} \left[\frac{T}{T_{ref}} \right]^3 \exp \left[\frac{q \cdot Eg \left(\frac{1}{T_{ref}} - \frac{1}{T} \right)}{nK} \right] \dots \dots \dots \text{II.3}$$

$$I_{rs} = \frac{I_{cc}}{\exp \left(\frac{q \cdot V_{oc}}{n \cdot N_s \cdot K \cdot T} \right) - 1} \dots \dots \dots \text{II.4}$$

$$I_{sh} = \frac{v + I_{RS}}{R_{sh}} \dots \dots \dots \text{II.5}$$

Where:

I_{ph} : photocurrent;

I_{cc} : short-circuit current;

I₀ : saturation current;

I_{rs} : reverse saturation current of the diode;

I_{sh} : shunt current, i.e., current flowing through the shunt resistance;

V_{oc} : open-circuit voltage;

T_{ref} : reference temperature;

q : 1.6×10^{-19} C, elementary electric charge;

n : diode ideality factor;

N : 36, number of cells;

K : 1.3805×10^{-23} J/K, Boltzmann constant;

E_g : 1.12 eV, silicon band-gap energy;

K_i : 0.003, coefficient of I_{cc};

R_s : series resistance;

R_{sh} : shunt resistance.

II.3.2 Double-Diode Model

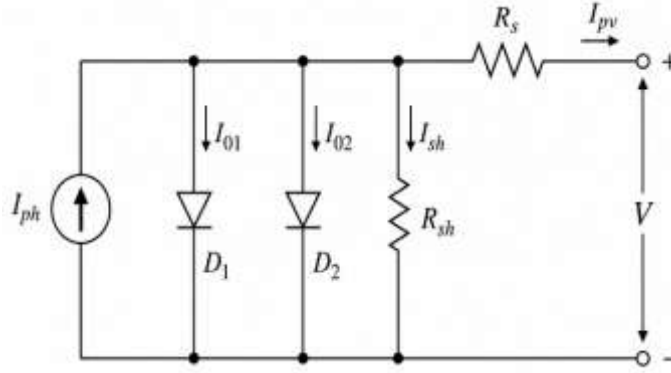


Figure (II.5): Equivalent electrical circuit of a solar cell (double-diode model).

The current is given by the following relation:

Where: n_1 and n_2 are the diode ideality factors; R_s is the series resistance; R_{sh} is the shunt resistance; G is solar irradiance; T is the cell temperature.

$$I_{pv} = I_{ph} - I_{01} \left[\exp \left(\frac{q(V + I R_s)}{n_1 K N_s T} \right) - 1 \right] - I_{02} \left[\exp \left(\frac{q(V + I R_s)}{n_2 K N_s T} \right) - 1 \right] - I_{sh} \dots \text{II.6}$$

$$I_{ph} = [I_{sc} + K_i(T - 298)] \frac{G}{1000} \dots \text{II.7}$$

$$I_{D1} = I_{rs1} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{q E_g}{n_1 K} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \dots \text{II.8}$$

$$I_{D2} = I_{rs2} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{q E_g}{n_2 K} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \dots \text{II.9}$$

$$I_{rs1} = \frac{I_{sc}}{\exp \left(\frac{q V_x}{M_1 K(T)} \right) - 1}; I_{rs2} = \frac{I_{sc}}{\exp \left(\frac{q V_x}{M_2 K(T)} \right) - 1} \dots \text{II.10}$$

$$I_{sh} = \frac{V + I R_s}{R_{sh}} \dots \text{II.11}$$

II.3.3 P-V and I-V Characteristics of Photovoltaic Modules at 1000 W/m² and 25°C

The I(V) and P(V) characteristics under standard conditions ($T = 25^{\circ}\text{C}$, $E = 1000 \text{ W/m}^2$) were obtained by simulation using MATLAB. The current-voltage I(V) and power-voltage P(V) characteristics of the photovoltaic cell are shown in the following figures:

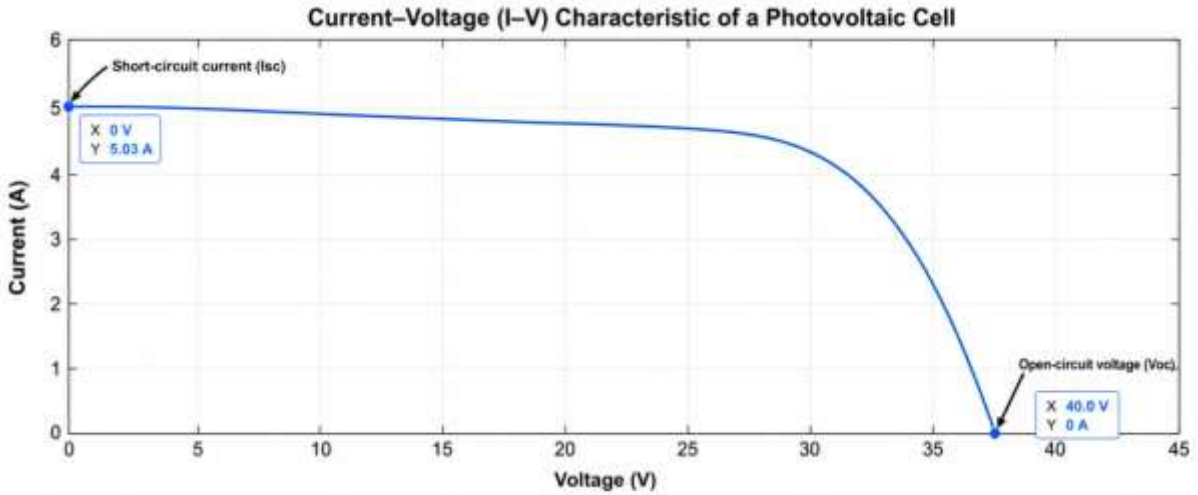


Figure (II.5): I-V characteristic of photovoltaic modules at 1000 W/m² and 25°C.

The first figure represents the current-voltage characteristic of a solar cell under $E = 1000 \text{ W/m}^2$ and $T = 25^{\circ}\text{C}$. The short-circuit current is 5.06 A and the open-circuit voltage is 21.96 V.

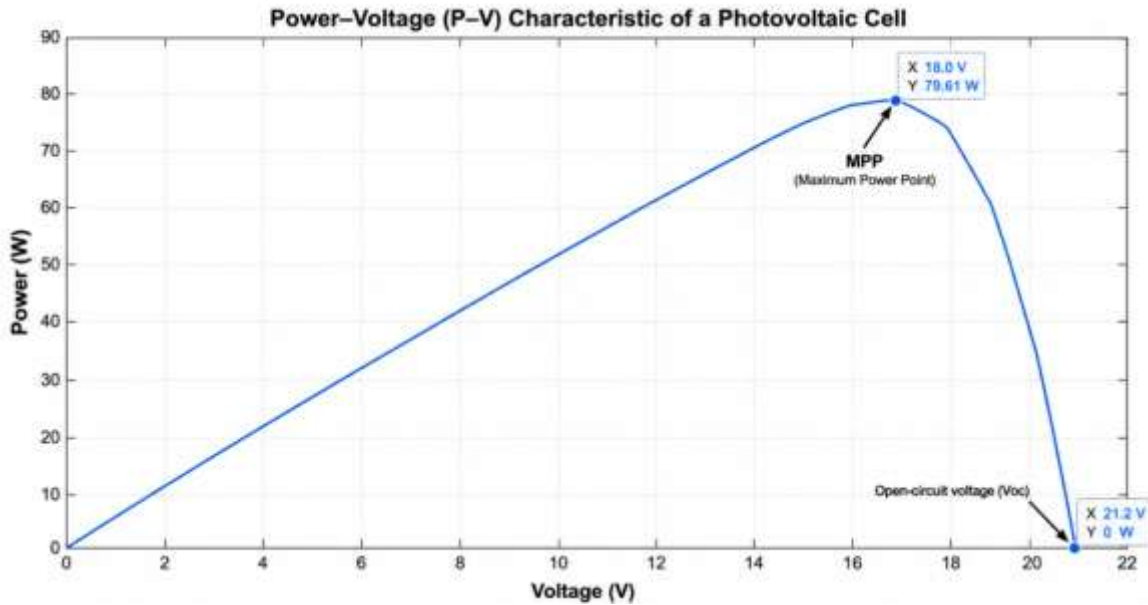


Figure (II.6): P-V characteristic of photovoltaic modules at 1000 W/m² and 25°C.

The second figure represents the power-voltage characteristic of a solar cell under $E = 1000 \text{ W/m}^2$ and $T = 25^\circ\text{C}$. The maximum power is $P_{\text{max}} = 80 \text{ W}$. It can be observed that as voltage increases, power increases until it reaches the optimal value P_{max} , and then it decreases.

The study is carried out on a photovoltaic panel composed of 36 multicrystalline cells connected in series to form one branch. Two branches are then connected in parallel to produce a maximum power of 80 W.

II.4.Grid-Connected Solar PV Systems: Parallel and Series Configurations

II.4.1. Series Connection of Photovoltaic Cells

In a series configuration, the same current flows through all the cells, and the resulting characteristic of this arrangement is obtained by adding the voltages for a given current. Figure II.6 presents the resulting characteristic (ICS, VOC) obtained by connecting NS identical cells (IC, VC) in series [16].

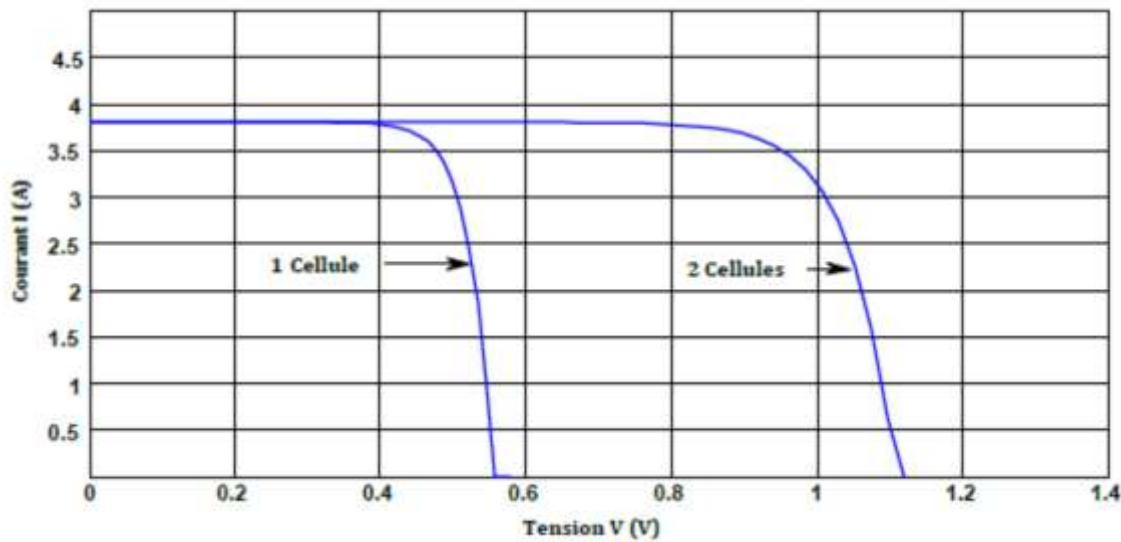


Figure (II.7): I-V characteristic of two photovoltaic cells connected in series.

II.4.2. Parallel Connection of Photovoltaic Cells

The properties of cells connected in parallel are the opposite of those of cells connected in series. Thus, in a parallel configuration, the cells are subjected to the same voltage, and the resulting characteristic is obtained by adding the currents for a given voltage. Figure II.7 illustrates the resulting characteristic (ICP, VCP) obtained by connecting NP identical cells (IC, VC) in parallel [16]:

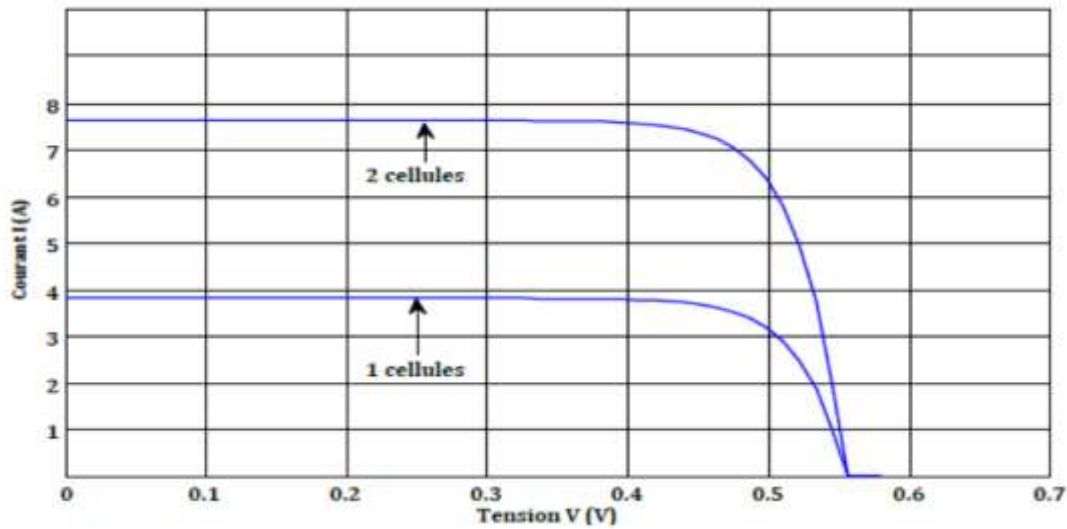


Figure (II.8): I-V characteristic of two photovoltaic cells connected in parallel.

II.5 Influence of Meteorological Parameters on the Operation of the PV Generator

The following figures represent the current-voltage $I(V)$ and power-voltage $P(V)$ characteristics under the same irradiance condition ($E = 1000 \text{ W/m}^2$) and for different temperatures ($T = 25^\circ\text{C}$, 60°C , and 85°C).

II.5.1 Influence of Temperature on the Cell

The open-circuit voltage decreases as temperature increases. By contrast, the short-circuit current increases slightly with temperature, while the maximum power decreases. Therefore, temperature has a negative influence on the open-circuit voltage.

II.5.1.1 I-V Characteristic

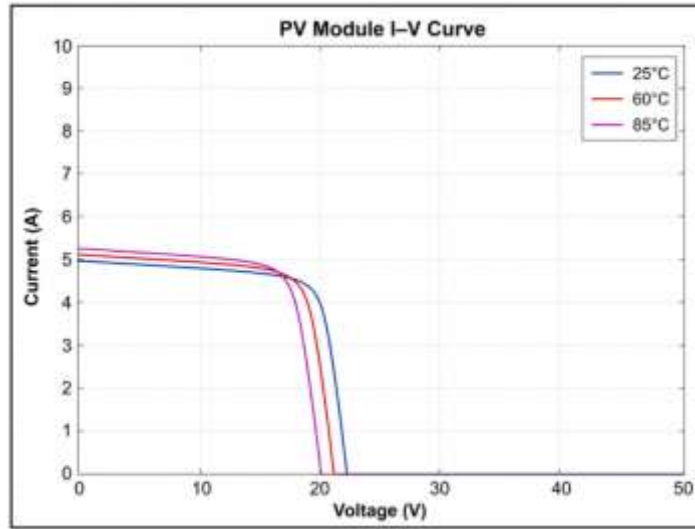


Figure (II.7): $I(V)$ characteristic for different temperatures ($G = 1000 \text{ W/m}^2$).

II.5.1.2 P-V Characteristic

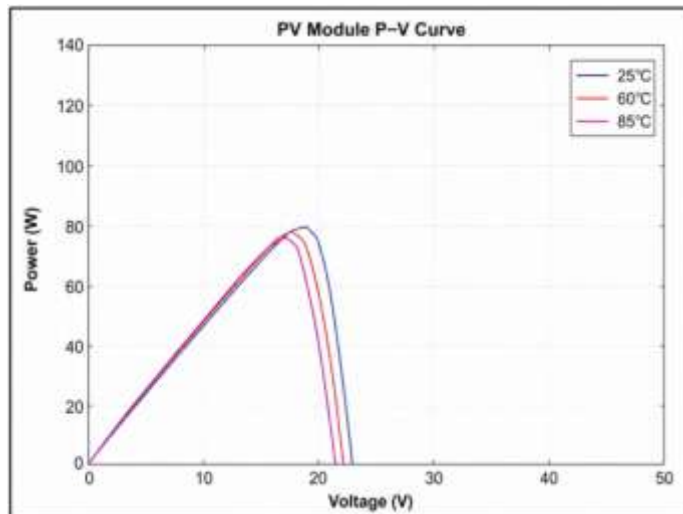


Figure (II.8): $P(V)$ characteristic for different temperatures ($G = 1000 \text{ W/m}^2$).

The following conclusion can therefore be drawn: PV cells perform better in a cold environment with a clear sky.

II.5.2 Influence of Irradiance on the Cell

The following figures represent the I-V and P-V characteristics of a cell as a function of irradiance variation ($E = 500, 750, \text{ and } 1000 \text{ W/m}^2$) at a constant temperature ($T = 25^\circ\text{C}$). The short-circuit current is directly proportional to the incident radiation. Conversely, the open-circuit voltage increases rapidly for low irradiance levels and then varies more slowly.

II.5.2.1 I-V Characteristic

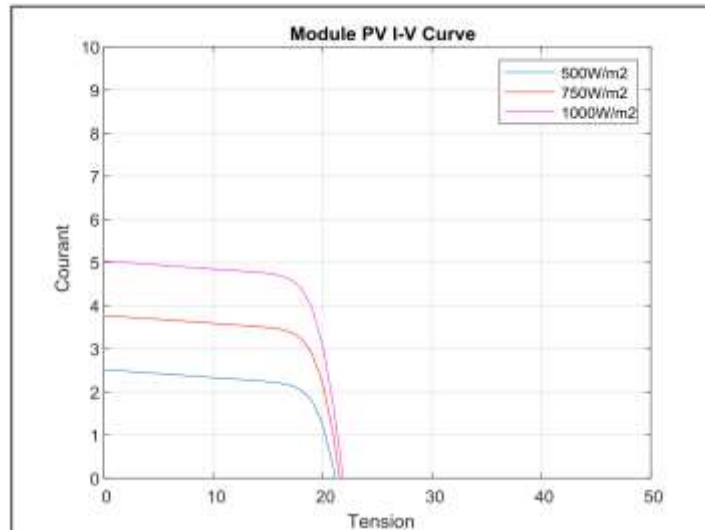


Figure (II.9): $I(V)$ characteristic for different irradiance levels ($T = 25^\circ\text{C}$).

II.5.2.2 P(V) Characteristic

Figure (II.10) illustrates the variation of the power delivered by the cell as a function of voltage for different irradiance values. This makes it possible to deduce the influence of irradiance on the P(V) characteristic. It can be observed that increasing irradiance causes an increase in power.

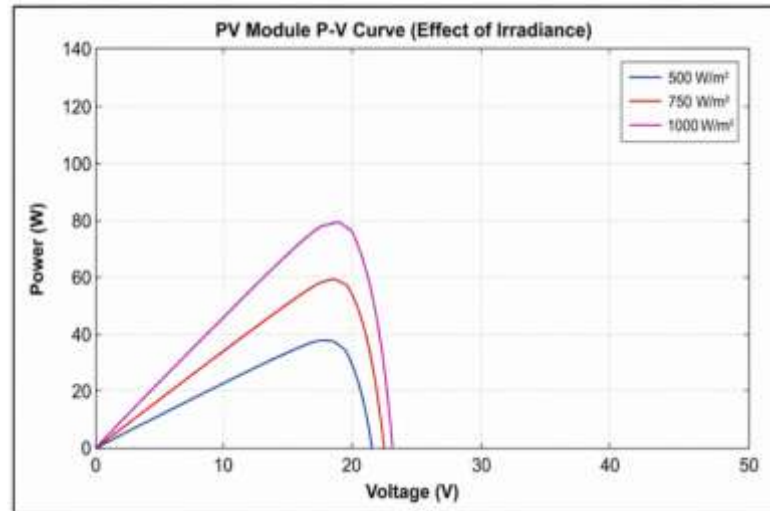


Figure (II.10): $P(V)$ characteristic for different irradiance levels ($T = 25^\circ\text{C}$).

II.6 Shading

II.6.1 Definition of Shading

Photovoltaic modules are very sensitive to shading. Unlike solar thermal panels, which can tolerate a certain amount of shade, photovoltaic modules should not be shaded, mainly because of the electrical connections in series between cells and between modules.

Two types of shading are distinguished: total shading and partial shading. Complete shading prevents all radiation, direct and indirect, from reaching part of the photovoltaic cell, for example bird droppings, a tree branch on the panel, or a covering. Partial shading prevents only direct radiation from reaching part of the photovoltaic cell, for example a chimney, a tree, or a cloud. Often, the cells of a photovoltaic module are connected in series. Thus, the weakest cell determines and limits the power of the other cells. Shading half of a cell or half of a row of cells reduces the power in proportion to the percentage of shaded area of a cell; in this case, 50%. Total shading of one row of cells can reduce the module power to zero. [10]

II.6.2 Shading Phenomenon on Photovoltaic Modules

Adding voltages in the case of a series assembly of PV cells is simple if all the cells are identical and operate under the same irradiance and temperature conditions. However, as stated previously, under real operating conditions, if the cells are slightly different or are not uniformly illuminated, the electrical behavior is not easily predictable and depends on the characteristics of

each cell and on the irradiance conditions. Several studies have presented mathematical models to calculate the effects of non-identical cells in a module. Figure (II.11) shows the I-V characteristic of a PV cell over its entire voltage range. It can be observed that, for a given solar irradiance and ambient temperature, if the current passing through a cell is greater than its short-circuit current, the cell operates in reverse-bias conditions with a negative voltage. In this case, excessive power is dissipated as heat in the shaded cell, and the cell or its encapsulation may be irreversibly damaged. This effect is called a “hot spot.” [11]

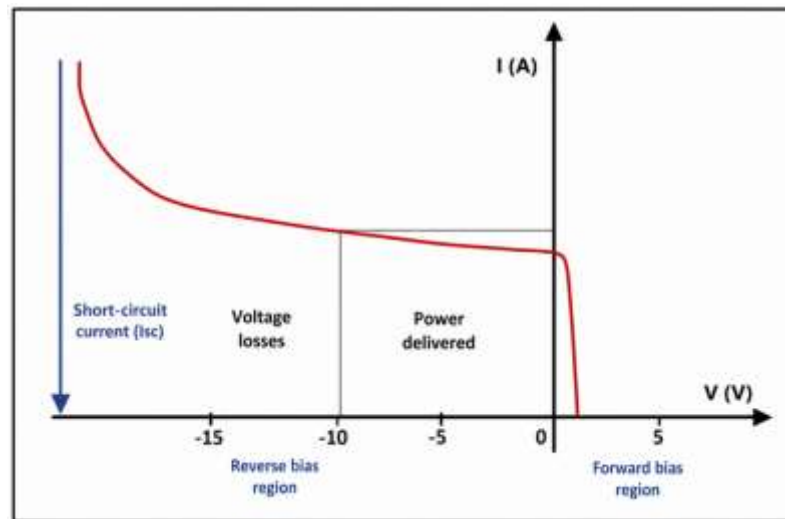


Figure (II.11): I-V characteristic of a PV cell.

In the forward-bias domain, which corresponds to normal operation, the open-circuit voltage of a crystalline cell is about 0.6 V, whereas in reverse bias the voltage can reach more than -20 V in the case of silicon. In a series assembly, the current is the same in all cells. If the string current is greater than the photocurrent of the shaded cell, which occurs in most cases, the shaded cell operates in reverse mode and dissipates power. This situation is illustrated in Figure (II.12) for three cells connected in series. [11]

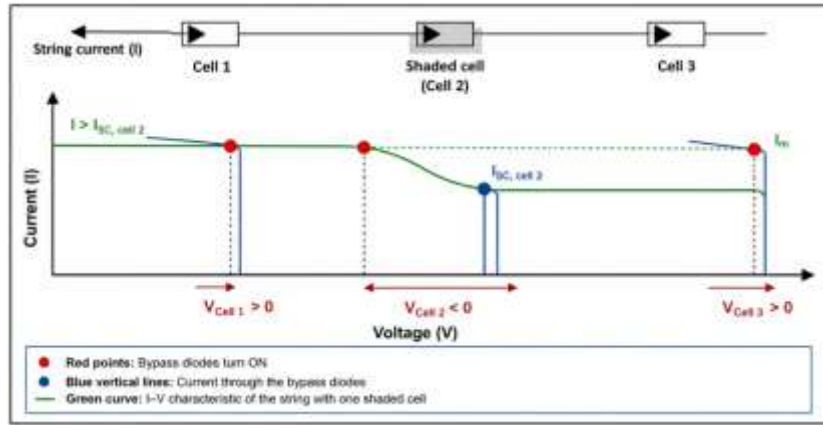


Figure (II.12): Characteristics of PV cells for a given current in the presence of shading.

If the row of cells operates at a point corresponding to a current I_m beyond the short-circuit current of the shaded cell (cell 2), the module operating point corresponds to a negative voltage across the shaded cell. This causes energy dissipation. To solve this problem, a bypass diode is connected in parallel across each series connection of multiple PV cells. If a bypass diode were connected to each cell, the problem caused by shading would be greatly reduced. However, this is not a commercially practical solution. [11]

II.6.3 Solutions to Limit the Impact of Shadows on Photovoltaic Panels

A. Type of Panel

One might imagine that when a leaf remains stuck on a panel, only the area of photovoltaic cells under the leaf stops producing electricity. This is not the case. In fact, a photovoltaic panel is generally divided into three distinct electrical zones (1/3, 1/3, and 1/3). When a leaf remains blocked on a solar panel, one third of the panel no longer produces electricity. The loss can even reach 60% or 100% if the obstruction is located on the side of the panel, blocking the beginning of the three lines.

Some panels are designed so that energy circulates in independent and parallel rows and also includes a grid, namely six horizontal rows and three vertical columns. With these panels, there are 18 distinct zones instead of 3. Consequently, the blocked leaf penalizes only 6% of photovoltaic production, or one third if the obstruction is on the side of the panel and blocks the beginning of the lines. [12]

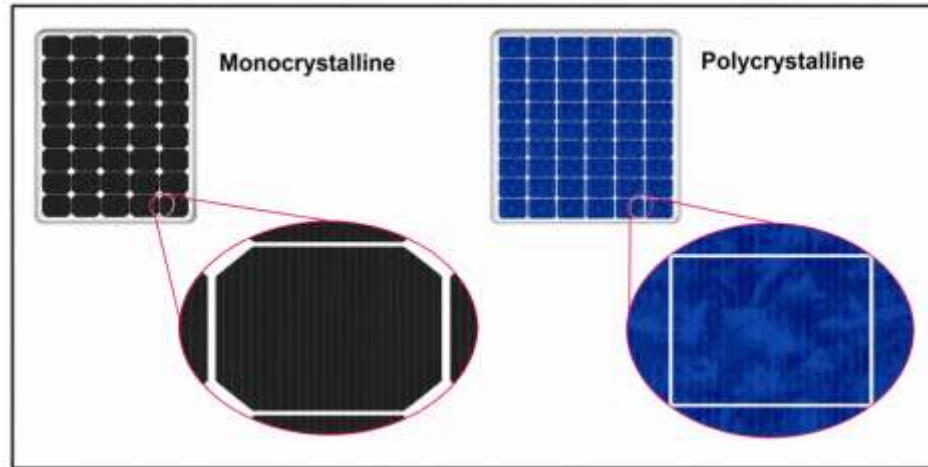


Figure (II.13): Some types of panels.

B. Microinverters

Inverters and microinverters are used to transform the direct current produced by photovoltaic panels into alternating current that can be used by appliances inside the house. When the photovoltaic installation is connected to a single central inverter, the malfunction of one panel blocks the entire production.

Installing microinverters on each panel allows all the other panels to continue operating normally if one panel malfunctions. Only the affected panel will have reduced production. [12]

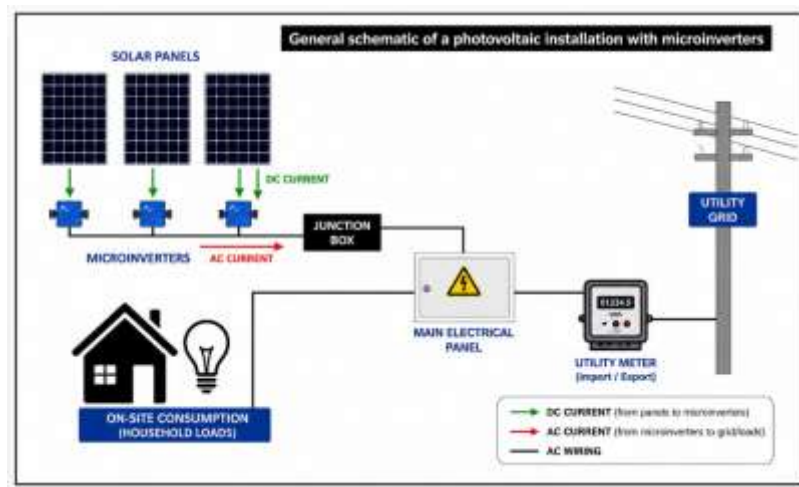


Figure (II.14): Microinverter installation diagram.



Figure (II.15): IQ7 microinverter.

C. Positioning and Installation Orientation of Panels

It is very important to study the position of photovoltaic panels by examining the shadows cast throughout the year, not only in summer, because in winter shadows are different and longer. Neighboring houses, trees, and chimneys can create shade.

Landscape orientation can also optimize energy production, since leaves often accumulate at the bottom of panels. Shadows can have very harmful consequences for electricity production. To prevent a small shadow from penalizing all photovoltaic panels, microinverters should preferably be used. They are more expensive to purchase but do not need to be replaced every ten years like a central inverter. Specialized photovoltaic panels should also be chosen. Finally, photovoltaic production should be checked regularly through a monitoring application and visually whenever possible. [12]

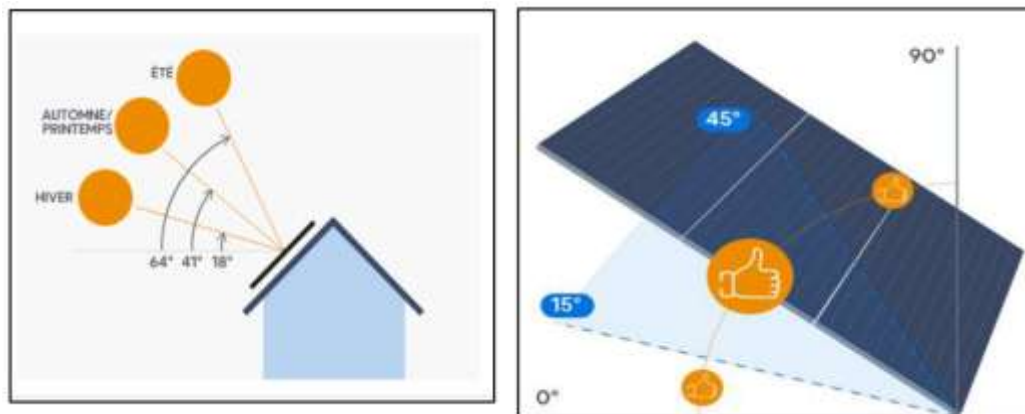


Figure (II.16): Inclination of solar panels.

II.7. Conclusion

In this chapter, the modelling of a photovoltaic module using the single-diode model was presented. The effect of meteorological variations, namely temperature and irradiance, on the produced energy was also examined. Finally, the phenomenon of partial shading and its effect on the PV panel were considered.

Chapter III:

Study of the adaptation stage

III.1 Introduction

The design of an adaptation stage makes it possible to connect a photovoltaic generator (PVG) to a direct-current (DC) load with a very high conversion efficiency. In practice, this stage represents the idealized basic functions of a DC-DC switching converter. It is called an adaptation stage because it links the four electrical quantities at its input and output ports: input voltage, input current, output voltage, and output current.

III.2 Principle of Maximum Power Point Tracking (MPPT)

A photovoltaic generator has an operating point at which the delivered power is maximum. Optimization consists of maintaining this point continuously by automatically acting on the load seen by the generator. In principle, this load adaptation is generally achieved by means of a static converter whose losses must be as low as possible. The converter may also perform the function of shaping the output power. Different approaches can therefore be considered for controlling the adapter. [13]

This type of control is commonly known as Maximum Power Point Tracking (MPPT). Figure (III.1) shows a basic photovoltaic conversion chain associated with an MPPT control. To simplify the operating conditions of this control, a DC load is selected. In solar conversion, the adapter can be implemented using a DC-DC converter so that the power supplied by the PVG corresponds to the maximum power it can generate, before being transferred directly to the load [13], [14], [15].

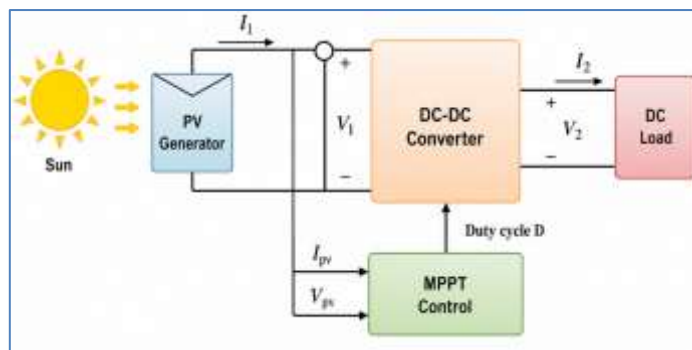


Figure (III.1): Principle diagram of the MPPT converter.

The commonly used control technique consists of automatically acting on the duty cycle in order to bring the generator to its optimal operating value, regardless of meteorological instabilities or sudden load variations.

III.3 MPPT Management

Figure (III.2) illustrates three disturbance cases. Depending on the type of disturbance, the operating point moves from the first maximum power point MPP1 to a new operating point P1 that may be more or less far from the optimum.

In the case of a change in irradiance, it is sufficient to readjust the duty-cycle value in order to converge toward the new maximum power point MPP2.

In the case of a change in the operating temperature of the PV generator, action is also required at the control level.

In the case of a load variation, the operating point is modified, but it can recover a new optimal position through the action of the control system.

In summary, MPP tracking is achieved by a specific control called MPPT. This control mainly acts on the duty cycle of the static converter (SC) to search for and reach the MPP of the PV generator. Several MPPT operating principles exist, with different performance levels depending on the properties of the PV generator [16].

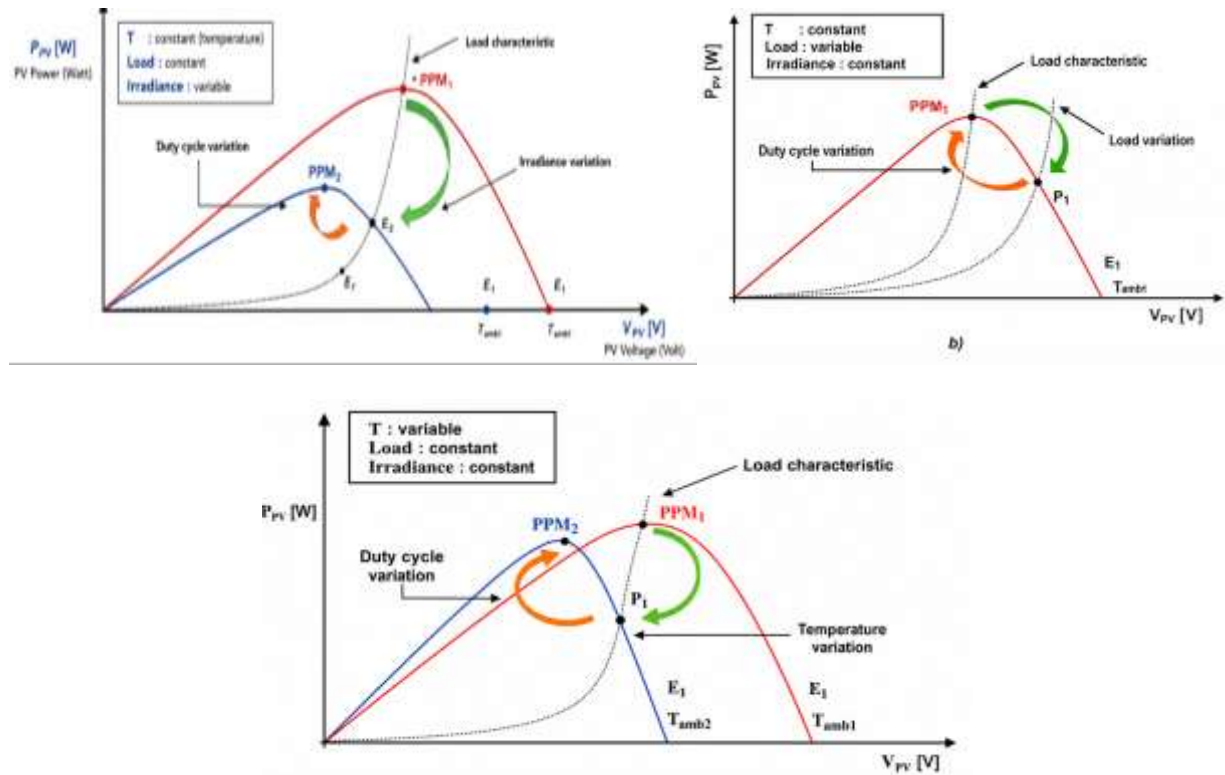


Figure (III.2): Search and recovery of the maximum power point.

III.4 MPPT Control

In order to obtain a better output voltage from a converter, it is necessary to control the converter switches. This is achieved using one of the available control techniques. The choice of the technique depends mainly on the intended application of the device. Several control types are used for converters, including analog control, generally based on operational amplifiers, and digital control, generally based on programmable integrated circuits such as microcontrollers. The latter is the type of control used for the converter considered in this work. MPPT control provides more reliable control signals and uses operating principles that are more or less efficient depending on the properties of the PV generator [17].

III.4.1 Principle of MPPT Control

By definition, an MPPT control associated with an intermediate adaptation stage allows a PV generator to operate so that it continuously produces its maximum power, whatever the meteorological conditions such as temperature and irradiation. The converter control places the system at the maximum operating point, defined by V_{MPP} and I_{MPP} . On the power curve shown in Figure (III.3), the output power delivered by the module is the product of voltage and current. At both ends of the I-V curve, the output power is zero because either the current or the voltage is zero. The maximum power point is the point on the curve where the product of current and voltage reaches its maximum [18].

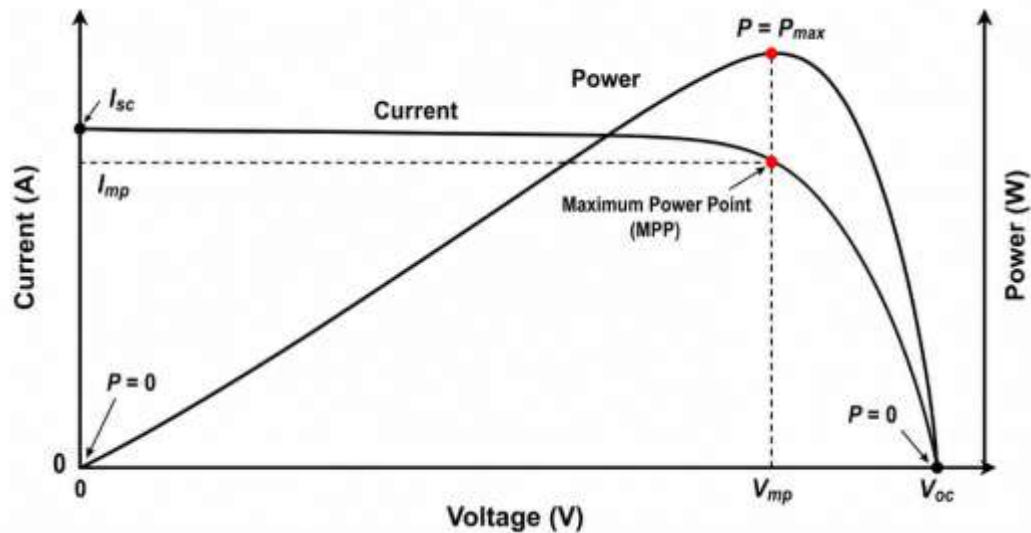


Figure (III.3): I-V curves and output power curve for a photovoltaic module.

The MPPT control varies the duty cycle of the static converter using an appropriate electrical signal in order to extract the maximum power that the PV generator can deliver. This duty-cycle variation depends on the evolution of the converter input parameters, namely current, voltage, and therefore PV power, until the operating point is placed on the MPP [19].

III.5 Classification of Maximum Power Point Tracking Algorithms

The classification of tracking algorithms may be based on the function of the techniques or on the control strategies used. Accordingly, two categories can be identified: indirect methods and direct methods.

III.5.1 Indirect Methods

Indirect methods use databases containing the characteristics of PV panels under different climatic conditions, such as temperature and irradiance. They may also use empirical mathematical equations to determine the maximum power point. These methods are often specific to each panel type and are therefore difficult to generalize. Examples include the curve-fitting method, the look-up table method, the open-circuit voltage method, and the short-circuit current method.

III.5.1.1 Open-Circuit Voltage Method of the PV Generator

This algorithm is based on the fact that the voltage of the PV generator at the maximum power point is approximately proportional to its open-circuit voltage. The proportionality constant $K1$ depends on the photovoltaic cell technology, the fill factor, and the meteorological conditions. The open-circuit voltage V_{oc} is measured by periodically interrupting the normal operation of the system. The data are stored and the MPP is then calculated using the following relationship:

$$K^1 = \frac{V_{MPP}}{V_{oc}} \approx \text{constant} < 1 \dots\dots\dots \text{III.1}$$

The operating voltage is then adjusted to obtain the optimal voltage. This process is repeated periodically. Although this method is simple, it is difficult to choose an optimal value of $K1$ [20], [21]. Its advantage is that it does not directly account for the influence of irradiance, temperature, or panel aging. For this reason, it suffers from inaccuracy, but it remains simple and inexpensive [21].

III.5.1.2 Short-Circuit Current Method

This method is similar to the previous one. It is based on the proportionality between the short-circuit current and the current at the maximum power point, according to the following equation:

$$K2 = \frac{I_{MPP}}{I_{SC}} \approx \text{constant} < 1 \dots\dots\dots \text{III.2}$$

This method has the same advantages and disadvantages as the open-circuit voltage method.

III.5.2 Direct Methods

Direct methods use measurements of panel voltage and current, and their algorithms are based on the variation of these measured quantities. Their main advantage is that they do not require prior knowledge of the PV panel characteristics. Among these techniques are the differentiation method, Perturbation and Observation (P&O), and the Incremental Conductance method [21].

III.5.2.1 Perturbation and Observation (P&O) Method

The Perturbation and Observation method is one of the most widely used MPPT techniques. It is an iterative method for obtaining the MPP: the PV panel characteristics are measured, and then a small perturbation is applied to the voltage in order to analyze the resulting power variation. The principle of P&O MPPT control consists of perturbing the PV voltage V_{pv} by a small amplitude around its initial value and analyzing the behavior of the resulting power variation P_{pv} .

As shown in Figure (III.4), if a positive increment in V_{pv} produces an increase in P_{pv} , this means that the operating point is located to the left of the MPP. Conversely, if the power decreases, the system has already passed the MPP. The same reasoning can be applied when the voltage decreases. From this analysis, it becomes possible to locate the operating point relative to the MPP and to converge toward the maximum power point through an appropriate control command. In short, after a voltage perturbation, if the PV power increases, the direction of perturbation is maintained; otherwise, it is reversed in order to resume convergence toward the new MPP [21].

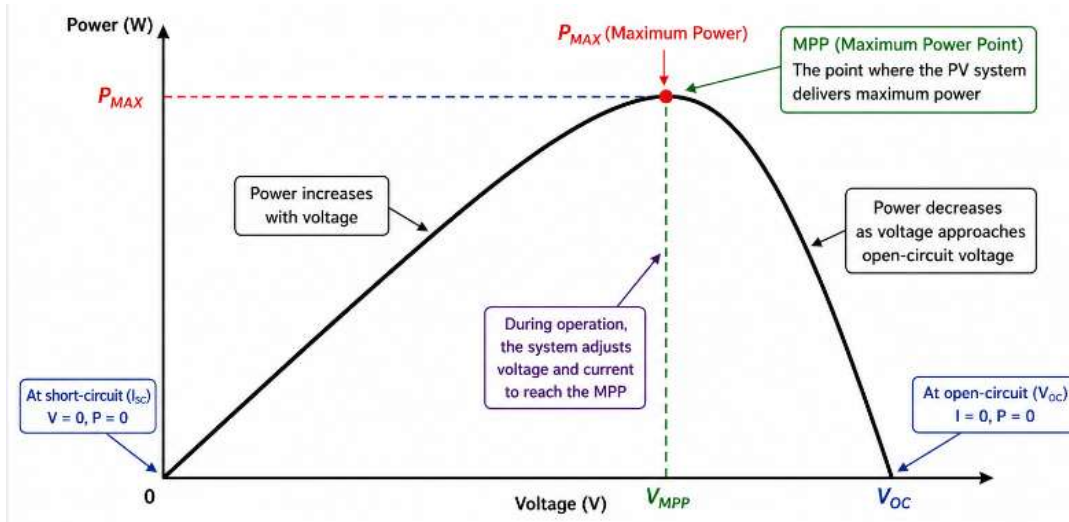


Figure (III.4): Convergence scheme toward the MPP using P&O.

Figure (III.5) shows the classical algorithm associated with P&O-type MPPT control, where power evolution is analyzed after each voltage perturbation. This type of control requires two sensors, one for PV current and one for PV voltage, in order to determine the PV power at every instant.

The P&O method is widely used because it is easy to implement. However, it has some drawbacks related to oscillations around the MPP in steady state, since the search procedure must be repeated periodically. These oscillations can be minimized by reducing the perturbation step. Nevertheless, a small step slows down the search for the MPP, which requires a compromise between accuracy and speed. This makes the control difficult to optimize. P&O gives good efficiency on relatively sunny days when the MPP evolves slowly and proportionally with solar radiation, but it can produce more losses during days with frequent and sudden irradiance changes because of the response time needed to reach the new MPP [21].

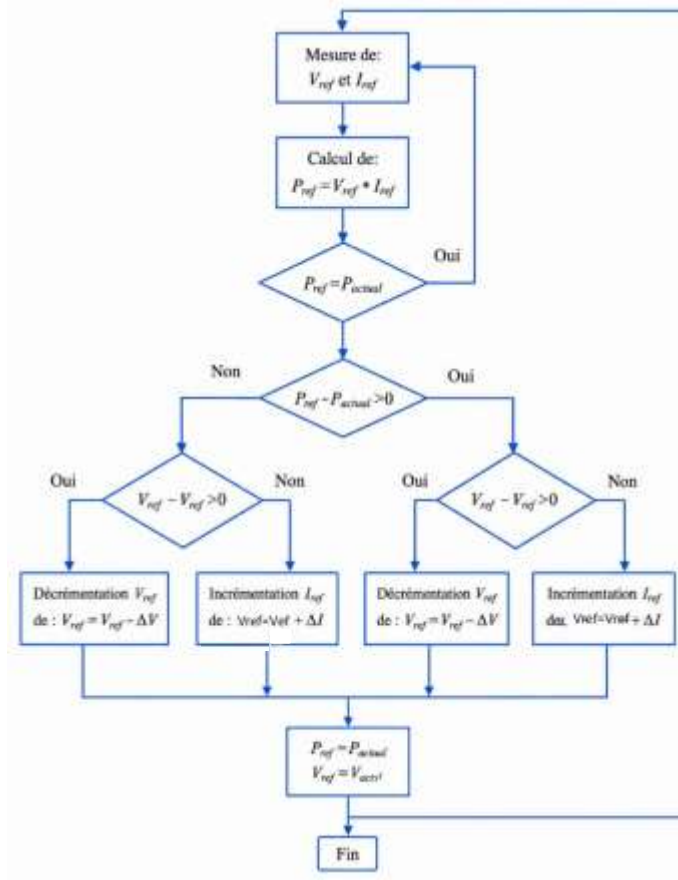


Figure (III.5): Typical flowchart of the P&O method.

III.5.2.2 Incremental Conductance Method

This method is directly concerned with variations of power as a function of voltage. The power produced by the PV generator can be expressed as:

$$P_{PV} = V_{PV} \cdot I_{PV} \dots \dots \dots \text{III.3}$$

The conductance and the increment of conductance can be identified by differentiating this equation with respect to the PV voltage V_{pv} :

$$\frac{1}{V_{PV}} \cdot \frac{dp_{pv}}{dv_{pv}} = \frac{I_{PV}}{V_{PV}} + \frac{dI_{PV}}{dv_{pv}} \dots \dots \dots \text{III.4}$$

At the maximum power point, this relation is equal to zero. This leads to the following set of conditions:

$$\frac{dp_{pv}}{dv_{pv}} = 0 \rightarrow \frac{dI_{PV}}{dv_{pv}} = -\frac{I_{pv}}{V_{pv}} \dots \dots \dots \text{III.5}$$

$$\frac{dp_{pv}}{dv_{pv}} > 0 \rightarrow \frac{dI_{PV}}{dv_{pv}} = -\frac{I_{PV}}{V_{PV}} \dots\dots\dots \text{III.6}$$

$$\frac{dp_{pv}}{dv_{pv}} < 0 \rightarrow \frac{dI_{PV}}{dv_{pv}} = -\frac{I_{PV}}{V_{PV}} \dots\dots\dots \text{III.7}$$

The principle consists of comparing the conductance $G = I_{pv} / V_{pv}$ with its derivative $\Delta G = dI_{pv} / dV_{pv}$, and then deciding whether to increase or decrease the PV voltage in order to reach the maximum power point where $dP_{pv} / dV_{pv} = 0$. The incremental conductance method is often considered effective for MPP tracking. However, the algorithm is more complex to implement and requires more computation, which can reduce the control period of the system [20], [22], [23].

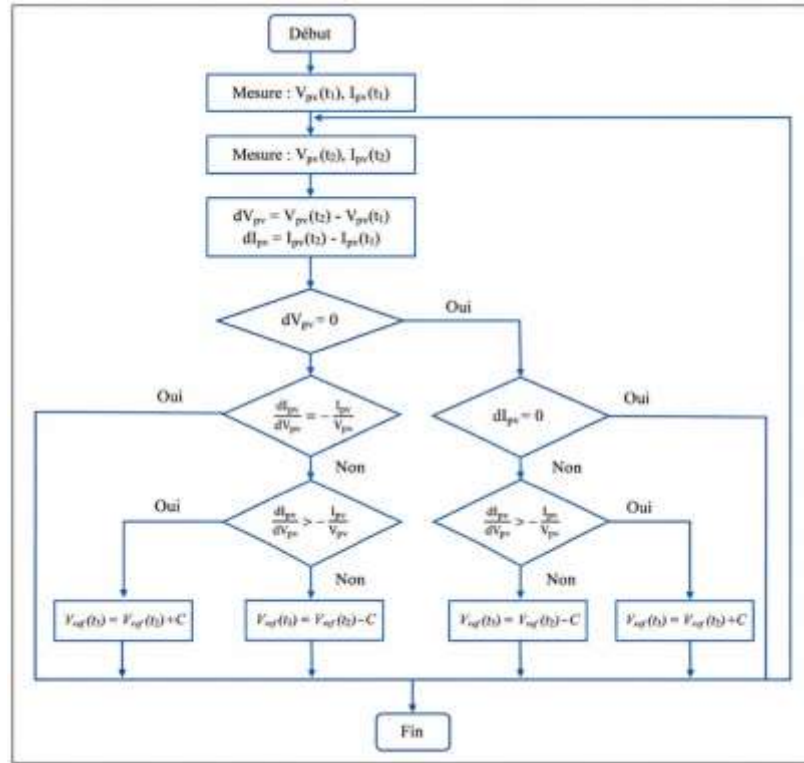


Figure (III.6): Flowchart of the incremental conductance method.

The operating point is on the MPP. The operating point is to the left of the MPP. The operating point is to the right of the MPP.

III.5.2.3 Classical MPPT Control

A simple method often used in the literature consists of reaching the maximum power point when the slope dP_{pv} / dV_{pv} reaches the desired value, that is, zero. The control law that provides continuous extraction of the maximum power point can be written as:

$$V_{opt} = k \cdot \int \frac{dP_{pv}}{dV_{pv}} \cdot dt = k \cdot \int \frac{\Delta P_{pv}}{\Delta V_{pv}} \dots \dots \dots \text{III.8}$$

Where:

V_{opt} : optimal voltage corresponding to maximum power.

k : proportional gain.

dP_{pv} / dV_{pv} : variation of power with respect to voltage.

ΔP_{pv} : power variation between two operating points.

ΔV_{pv} : voltage variation between two operating points.

The functional control diagram is shown in the following figure:

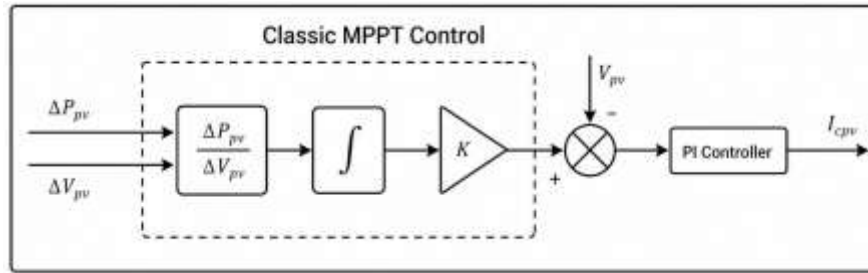


Figure (III.7): Functional diagram of the classical MPPT control.

III.6 DC-DC Converter (Chopper)

To convert solar energy with better efficiency, it is necessary to operate at the maximum power point. The photovoltaic generator delivers its full power at a well-defined operating point on the $I = f(V)$ characteristic. Ideally, the system should operate exactly at this point, but it fluctuates widely because of temperature and irradiance variations. To overcome this problem and increase the energy efficiency of the system, an electronic device based on a DC-DC converter is inserted between the PV generator and the load. Maintaining the operating point at the maximum power point is achieved by continuous control of the duty cycle of this power converter. However, this device requires careful attention in terms of sizing, control, and regulation in order to avoid system instability [24].

III.6.1 Converter Types

There are three main types of static converters:

III.6.1.1 Step-Down Chopper, or Buck Converter

A step-down chopper is obtained when the switch is placed in series with the load. It is used for low-voltage applications and converts a DC voltage into another DC voltage of lower value. In photovoltaic applications, this converter can be used as a source-load adapter when the direct-coupling operating point is far from the MPP. The Buck converter is usually used as a battery charger. Its basic diagram is given in the following figure [25].

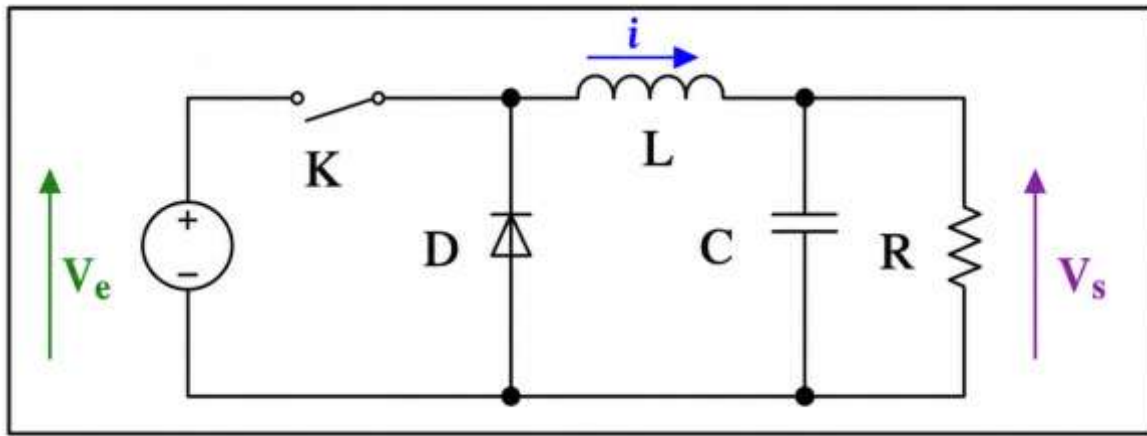


Figure (III.8): Step-down chopper, or Buck converter.

III.6.1.2 Step-Up Chopper, or Boost Converter

A step-up chopper is obtained when the switch is placed in parallel with the load. Its role is to convert a DC voltage into another DC voltage of higher value. This type of converter can be used to supply the grid through an inverter. Its basic diagram is shown in the following figure [25].

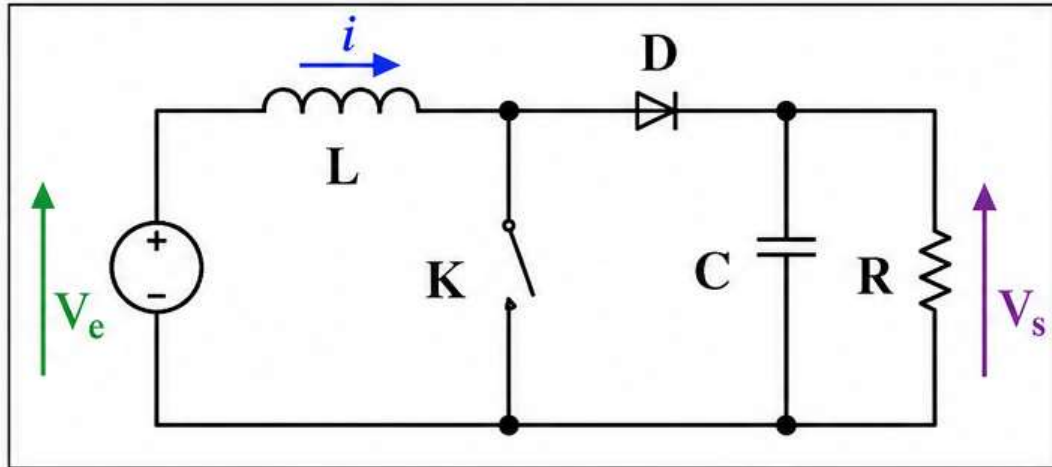


Figure (III.9): Step-up chopper, or Boost converter.

III.6.1.3 Buck-Boost Converter

The Buck-Boost converter combines the properties of the two previous converters. Its basic diagram is shown in the following figure [25].

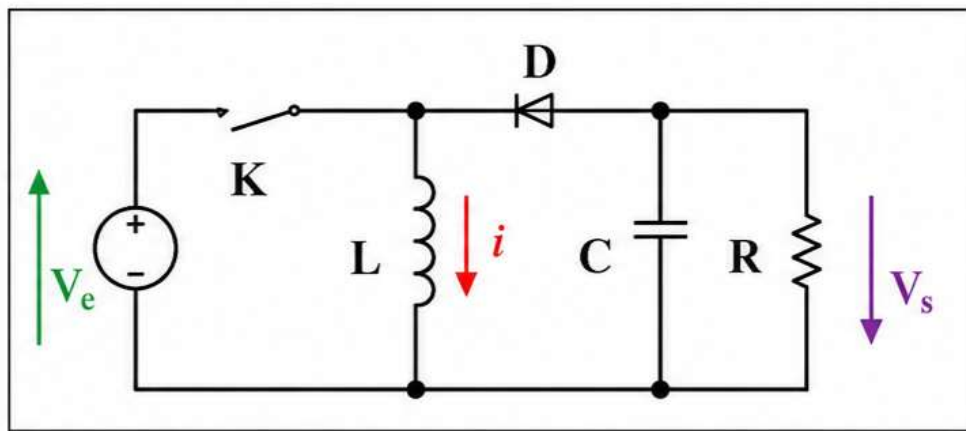


Figure (III.10): Buck-Boost converter.

III.7 Equivalent Mathematical Model

In order to synthesize the functions of the boost converter at equilibrium, it is necessary to present the equivalent circuit diagrams for each position of the switch K. Figure (III.12) presents the equivalent circuit of the boost converter when K is closed, that is, during the interval $t \in [0, \alpha Ts]$,

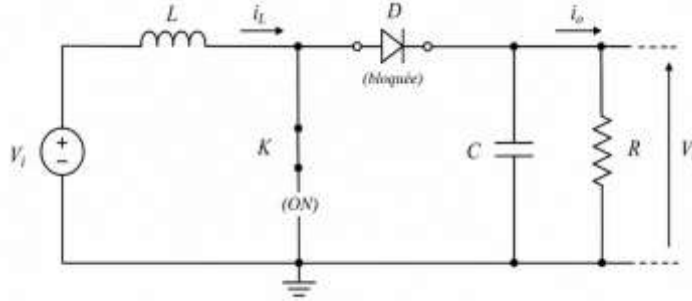


Figure (III.12): Equivalent diagram of the boost converter when $t \in [0, \alpha Ts]$.

As with the Buck circuit, applying Kirchhoff's laws to the equivalent circuits of the two operating phases gives:

$$i_{c1} = C_1 \frac{dv_i(t)}{dt} = i_i(t) - i_l(t) \dots\dots\dots \text{III.9}$$

$$i_{c2} = C_2 \frac{dv_o(t)}{dt} = -i_o(t) \dots\dots\dots \text{III.10}$$

$$v_l(t) = l \frac{di_l(t)}{dt} = v_i(t) \dots\dots\dots \text{III.11}$$

When the switch K is open, the equivalent boost circuit is as follows:

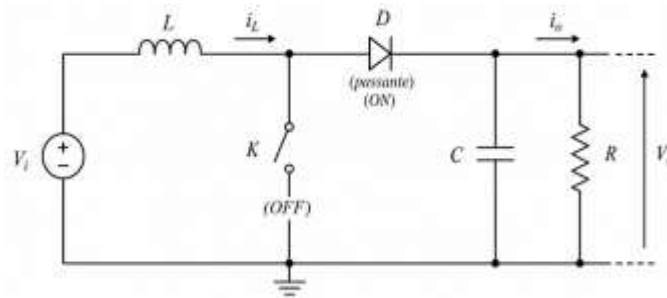


Figure (III.13): Equivalent diagram of the boost converter when $t \in [\alpha Ts, Ts]$.

$$i_{c1}(t) = c_1 \frac{dv_i(t)}{dt} = i_i(t) - i_l(t) \dots\dots\dots \text{III.12}$$

$$i_{c2}(t) = c_2 \frac{dv_o(t)}{dt} = i_l(t) - i_o(t) \quad v_l(t) = l \frac{di_l}{dt} = v_i(t) - v_o(t) \dots\dots\dots \text{III.13}$$

The input inductance is chosen sufficiently high to smooth the input current.

III.8 Conclusion

This chapter examined the principle of maximum power point tracking (MPP) for different algorithms. It also reviewed several DC-DC converter types used as adaptation stages. Finally, it recalled the operation of MPPT control and presented some existing algorithms used for tracking the maximum power point.

Chapter IV

Simulation and results discussion

IV.1 Introduction

After reviewing the theoretical foundations of photovoltaic energy (Chapter I), modeling of the solar system with the influence of temperature and irradiance (Chapter II), and the principle of Maximum Power Point Tracking (MPPT) along with DC-DC converters used in the adaptation stage (Chapter III), this fourth chapter is dedicated to **simulation and results discussion**.

The main objective of this chapter is to study the **effect of partial shading on the electrical power produced by a photovoltaic module**, using a suitable simulation environment (MATLAB/Simulink,). The simulation will be based a photovoltaic module capable of producing a maximum power of **83.28 Watts** under standard test conditions (STC).

The simulation scenario will compare the performance of the PV module under two different conditions:

1. **Uniform illumination (no shading):** The P-V curve presents a single peak, allowing conventional MPPT algorithms (such as Perturb & Observe) to operate efficiently.

2. **Partial shading condition:** A portion of the PV module is shaded, which – as expected – will lead to complex I-V and P-V curves exhibiting **multiple peaks**. This situation reveals the limitation of conventional MPPT algorithms, which cannot distinguish between local and global maximum power points. This challenge will be discussed, and potential mitigation solutions will be proposed.

At the end of this chapter, the simulation results will be presented and analyzed graphically, demonstrating the impact of shading on energy production and highlighting the importance of choosing an appropriate MPPT algorithm for partially shaded conditions.

IV.2 Simulation Environment

The simulation was carried out using the MATLAB/Simulink environment in order to analyze the effect of partial shading on the electrical performance of a photovoltaic array.

The studied PV system consists of six photovoltaic strings subjected to different irradiance levels varying from 200 W/m² to 900 W/m² while maintaining a constant temperature of 25°C.

Bypass diodes were included in the PV model to reproduce realistic operating conditions and to protect shaded cells from reverse bias effects.

The simulation mainly focuses on the analysis of the I-V and P-V characteristics under non-uniform irradiance conditions in order to evaluate the impact of partial shading on power generation and MPPT operation.

Module data		Model parameters	
Module: User-defined		Light-generated current I_L (A)	
Maximum Power (W)		8.6307	
83.2824	Cells per module (Ncell)	Diode saturation current I_0 (A)	
	20	1.4176e-10	
Open circuit voltage V_{oc} (V)		Diode ideality factor	
37.92*20/60	Short-circuit current I_{sc} (A)	0.99132	
	8.62	Shunt resistance R_{sh} (ohms)	
Voltage at maximum power point V_{mp} (V)		82.1161	
30.96*20/60	Current at maximum power point I_{mp} (A)	Series resistance R_s (ohms)	
	8.07	0.098625	
Temperature coefficient of V_{oc} (%/deg.C)			
-0.33969	Temperature coefficient of I_{sc} (%/deg.C)		
	0.063701		

Figure IV.1 : Electrical parameters of the photovoltaic module used in the simulation

IV.2.1 Characteristics of the photovoltaic module

The technical characteristics of the photovoltaic module used in this simulation are presented in the table above (Figure IV.1). This module consists of 20 cells connected in series.

The nominal parameters under standard test conditions (STC: 1000 W/m², 25°C) are as follows:

- Maximum power (P_{max}) : 83.28 W
- Open circuit voltage (V_{oc}) : 12.64 V *(since $37.92 \times 20/60 = 12.64$ V)*
- Short circuit current (I_{sc}) : 8.62 A
- Voltage at maximum power point (V_{mp}) : 10.32 V *(since $30.96 \times 20/60 = 10.32$ V)*
- Current at maximum power point (I_{mp}) : 8.07 A

This module will be used as a PV generator in all simulations of Chapter IV. It will allow us to study the effect of partial shading on its electrical production.

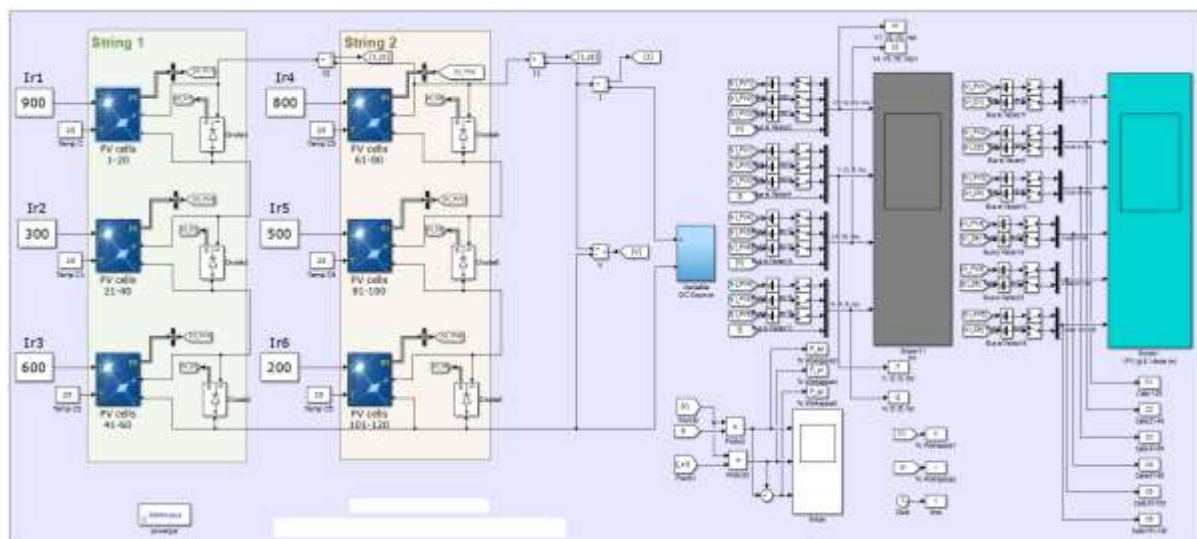


Figure IV.2 : Partial shading scenario applied to the PV array

Configuration of irradiance levels across six sub-strings of 20 cells each

String	Cells	Irradiance (W/m ²)	Temperature (°C)
1	1 – 20	900	25
2	21 – 40	300	25
3	41 – 60	600	25
4	61 – 80	800	25
5	81 – 100	500	25
6	101 – 120	200	25

Interpretation:

The PV array is subjected to **non-uniform partial shading**. The significant variation in irradiance (from 200 to 900 W/m²) will lead to current mismatch between series-connected cells. Consequently, the P-V characteristic is expected to exhibit **multiple local peaks and one global peak**, which poses a serious challenge for conventional MPPT algorithms (P&O, IncCond) that are designed for single-peak curves. This scenario allows us to evaluate and compare the performance of different MPPT techniques under realistic shading conditions.

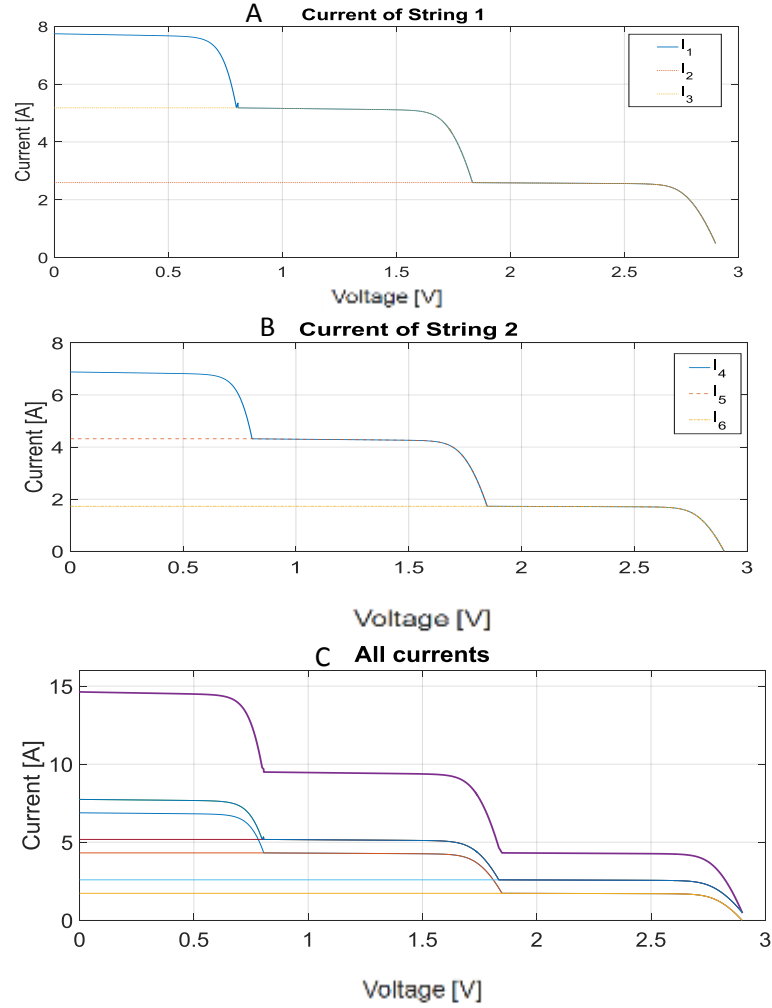


Figure IV.3 : I-V characteristics for three different partial shading patterns

A Current of String 1, B Current of String 2, C All currents

IV.3 I-V Characteristics Under Partial Shading Conditions

Figure IV.3 presents the I-V characteristics of the photovoltaic strings under different irradiance conditions caused by partial shading. It can be observed that the generated current varies significantly according to the applied irradiance level on each PV string.

The strings exposed to higher irradiance levels maintain higher current values, whereas the shaded strings produce lower currents due to the reduction in incident solar radiation. This mismatch between the PV string currents creates discontinuities (steps) in the global I-V characteristic.

These steps are directly related to the activation of bypass diodes, which protect the shaded cells from excessive reverse voltage and hot-spot phenomena. As the operating voltage increases, some shaded groups become bypassed, producing multiple transitions in the I-V curve.

The obtained results clearly demonstrate that partial shading strongly affects the electrical behavior of the photovoltaic array and significantly complicates the operation of conventional MPPT algorithms.

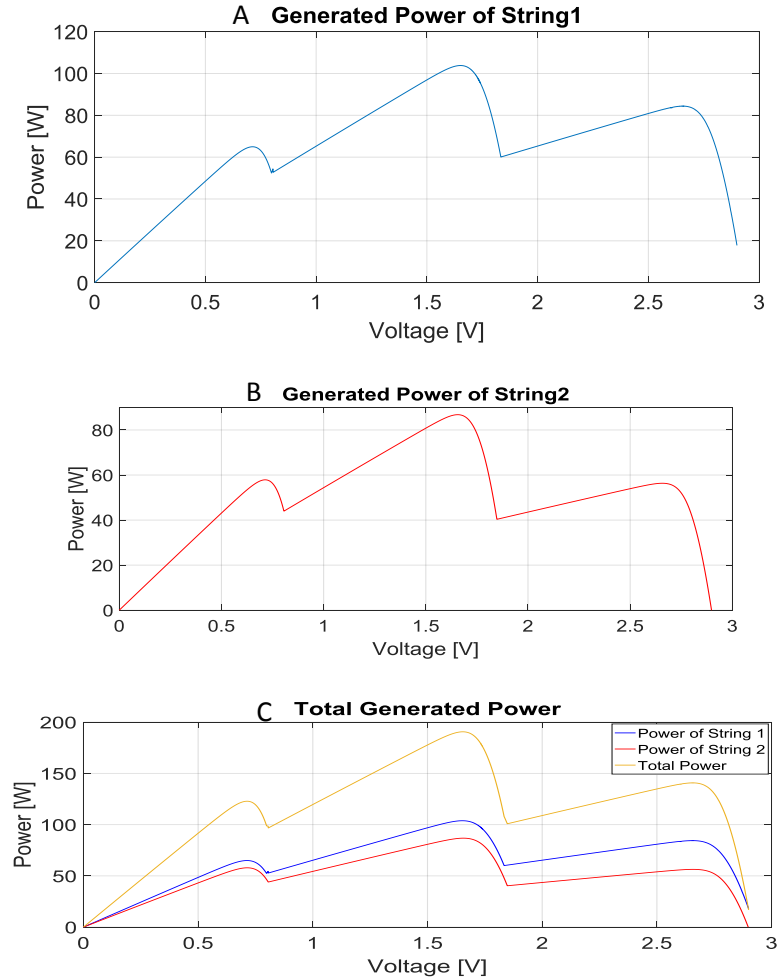


Figure IV.4 : Power-Voltage (P-V) characteristics under partial shading conditions

A Generated Power of String1, **B** Generated Power of String2, **C** Total Generated Power

IV.4 P-V Characteristics Under Partial Shading Conditions

Figure IV.4 illustrates the Power-Voltage (P-V) characteristic of the photovoltaic array operating under partial shading conditions.

Unlike the case of uniform irradiance, where the P-V curve contains a single maximum power point, the curve obtained under partial shading exhibits several local maxima and one global maximum power point (GMPP). This phenomenon is mainly caused by the mismatch between the currents generated by the shaded and unshaded PV strings.

The activation of bypass diodes creates several operating regions in the P-V characteristic. Consequently, multiple peaks appear at different voltage levels. The first local peaks correspond to partially active PV groups, whereas the global peak corresponds to the optimal operating condition of the entire PV array.

The simulation results confirm that conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) may fail under partial shading conditions. Since these algorithms are designed for single-peak curves, they may become trapped at a local maximum power point instead of tracking the true global maximum power point.

Therefore, partial shading considerably reduces the efficiency of classical MPPT techniques and requires the use of more advanced optimization methods capable of distinguishing between local and global maxima.

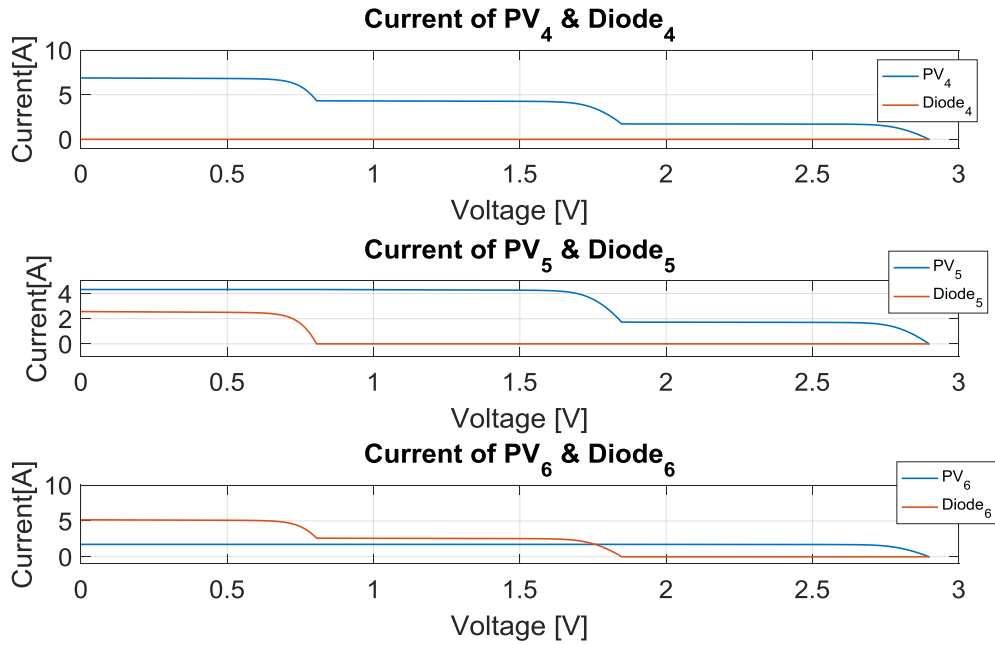


Figure IV.5 : Comparison of PV string current and bypass diode current under partial shading

IV.5 Effect of Bypass Diodes Under Partial Shading

Figure IV.5 illustrates the operation of bypass diodes in the photovoltaic array under partial shading conditions.

Under uniform irradiance, all PV cells generate approximately the same current, and the bypass diodes remain inactive. However, when some PV groups become shaded, their generated current decreases significantly compared with the unshaded groups.

In this situation, the bypass diodes become conductive in order to provide an alternative path for the current generated by the unshaded PV strings. This mechanism protects the shaded cells against reverse bias operation and prevents the appearance of hot spots that could permanently damage the photovoltaic module.

The activation of bypass diodes produces discontinuities in the I-V characteristic and generates multiple local maxima in the P-V curve. Consequently, the electrical behavior of the PV array becomes more complex under partial shading conditions.

The obtained results confirm that bypass diodes are essential for PV module protection, but they are also one of the main causes of the multi-peak phenomenon observed in partially shaded photovoltaic systems.

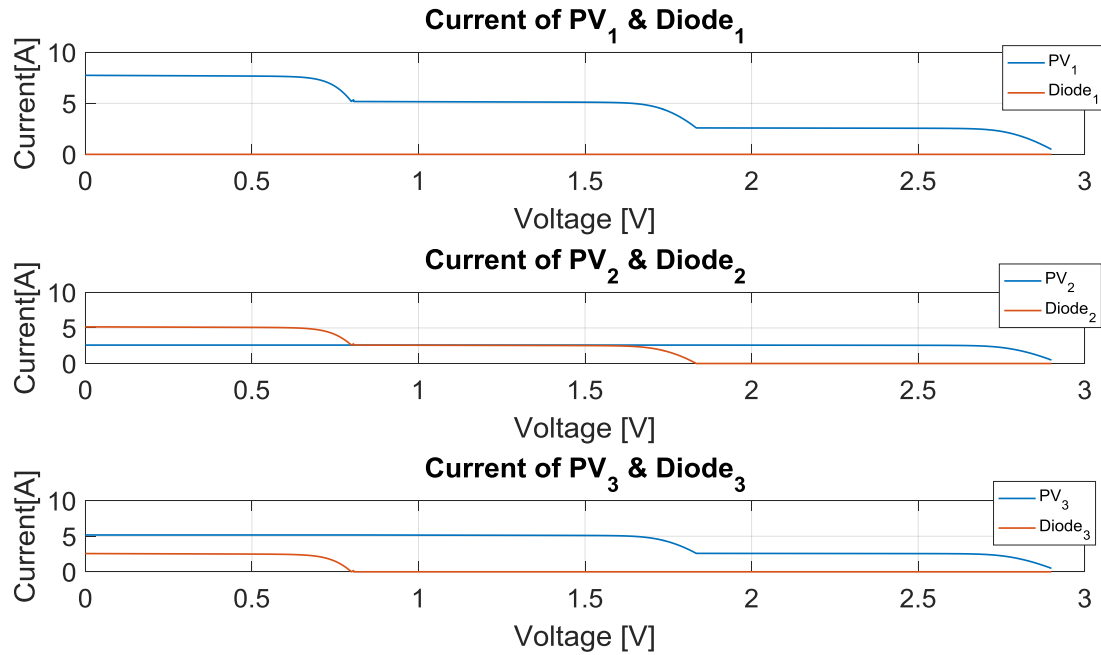


Figure IV.6 : Activation of bypass diodes at specific voltage levels under partial shading

IV.6 Comparison Between PV Current and Bypass Diode Current

Figure IV.6 compares the current generated by the photovoltaic strings with the current flowing through the associated bypass diodes under partial shading conditions.

The results show that the shaded PV strings are unable to generate the same current level as the unshaded strings. As a consequence, a portion of the total current flows through the bypass diodes instead of passing through the shaded photovoltaic cells.

This current redistribution confirms the protective role of bypass diodes in partially shaded PV systems. At the same time, it explains the appearance of multiple steps in the I-V characteristic and multiple peaks in the P-V characteristic.

The simulation demonstrates that the electrical behavior of the PV array under shading conditions becomes highly nonlinear and strongly dependent on the irradiance distribution across the different PV strings.

These results also explain why conventional MPPT techniques experience difficulties in locating the true global maximum power point under partial shading conditions.

IV.7 Conclusion

In this chapter, the effect of partial shading on the electrical performance of a photovoltaic array was investigated through simulation. Several shading scenarios were applied, and the resulting I-V and P-V characteristics were analyzed.

The results clearly show that partial shading transforms the single-peak P-V curve into a multi-peak curve containing one global maximum power point (GMPP) and several local peaks. This phenomenon is caused by the activation of bypass diodes, which protect the shaded cells but also create current steps in the I-V characteristic.

The comparison of PV string currents and bypass diode currents confirmed that under shading conditions, a significant portion of the total current flows through the bypass diodes rather than through the shaded PV cells.

Consequently, conventional MPPT algorithms such as Perturb & Observe (P&O) and Incremental Conductance (IncCond), which are designed for single-peak curves, are unable to distinguish between local and global peaks. They often become trapped at a local peak, resulting in a substantial loss of available power.

Therefore, for partially shaded PV systems, advanced MPPT techniques (e.g., global scan, Particle Swarm Optimization, or Fuzzy Logic) are necessary to ensure operation at the true global maximum power point. [26]

General Conclusion

General Conclusion:

This work focused on the effect of partial shading on the electrical power produced by photovoltaic panels. The study showed that photovoltaic energy is a clean and renewable source of electricity, but its efficiency remains strongly dependent on environmental and operating conditions. Among these conditions, partial shading has a particularly important impact because it directly affects the current, voltage, and power characteristics of the photovoltaic generator.

The theoretical study first presented the basic concepts of photovoltaic energy, including the operating principle of solar cells, the different types of photovoltaic technologies, and the main configurations of photovoltaic systems. It was shown that photovoltaic modules are sensitive to variations in irradiance and temperature, and that their output power decreases when operating conditions move away from standard test conditions.

The modelling part allowed a better understanding of the electrical behavior of the photovoltaic cell. The I-V and P-V characteristics showed that irradiance has a direct influence on the generated current and power, while temperature mainly affects the open-circuit voltage and reduces the maximum output power. These results confirm that the performance of photovoltaic panels depends on both the intensity of solar radiation and the thermal operating conditions.

The study of partial shading demonstrated that non-uniform irradiance causes a strong distortion of the electrical characteristics. Instead of having a single maximum power point, the P-V curve presents several peaks, including one global maximum power point and several local maximum power points. This phenomenon is mainly due to the activation of bypass diodes, which protect shaded cells from damage but also create steps in the I-V curve and multiple peaks in the P-V curve.

The simulation results confirmed that partial shading reduces the available power of the photovoltaic array and makes maximum power point tracking more difficult. Conventional algorithms such as Perturb and Observe or Incremental Conductance may become trapped at a local maximum point and fail to extract the maximum available energy. Therefore, more advanced MPPT techniques, such as global scanning, fuzzy logic, or optimization-based methods, are more suitable for photovoltaic systems operating under partial shading conditions.

In conclusion, partial shading represents a major challenge for photovoltaic energy production. Reducing its impact requires good installation design, appropriate panel orientation, the use of bypass diodes and microinverters when necessary, and the selection of efficient MPPT algorithms capable of detecting the true global maximum power point. Future work may focus on comparing advanced MPPT algorithms under different shading scenarios and validating the simulation results through experimental measurements on a real photovoltaic installation.

Bibliography

Bibliography:

- [1] Ben Ali Mohammed Elhabib and Krobba Ahmed Housseem Eddine, Study of the Control of Photovoltaic Panels Using an Intelligent Regulator, Master's thesis 2, Amar Telidji University of Laghouat, 2022/2023.
- [2] Zairi Soufiane and Boubiada Slimane, Study and Sizing of a Photovoltaic Power Plant, Master's thesis 2, University of Biskra, 13/09/2020.
- [3] Talbi Nabil and Chergui Aghiles, Integration of Solar Energy into Optimized Energy Management for a Building, University of Bejaia, 2019/2020. (PV operating mode).
- [4] <http://dspace.univ-tiaret.dz/bitstream/123456789/11514/3/chapitre%2001.pdf>.
- [5] Djaiou Salem and Aichouch Oussama, Use of Photovoltaic Energies in a Medical Analysis Laboratory (Ghardaia), Master's thesis 2, Saad Dahleb University - Blida 1, 2021/2022.
- [6] mypower.engie.fr, Types of Photovoltaic Solar Cells, published on 14/12/2021, updated on 22/02/2023, <https://mypower.engie.fr/conseils/panneaux-solaires/panneau-solaire-photovoltaique/types-cellules-solaires.html>.
- [7] Julien Reynaud, Photovoltaic Cells: An Inexhaustible Source of Innovation, published on 26/02/2021, updated on 17/06/2023.
- [8] M. Boukais, Modeling of the Photovoltaic Cell, University of Tiaret, 2017.
- [9] Shading, <https://www.ef4.be/fr/pv/composants-dun-systeme/ombrage.html>.
- [10] Benblidia Houssam and Kerkar Amar, Study of the Effect of Shading on a Photovoltaic System, Master's thesis 2, Saad Dahleb University of Blida, 2015.
- [11] L'Ombre sur les panneaux photovoltaïques [Shading on Photovoltaic Panels], 08/01/2023, <https://www.electron-solaire.fr/post/l-ombre-sur-les-panneaux-photovoltaïques>.
- [12] A. B. Learreta, Realization of Digital MPPT Controls, Final-Year Project, Rovira i Virgili University.
- [13] C. Cedric, Energy Optimization of the Electronic Adaptation Stage Dedicated to Photovoltaic Conversion, Doctoral thesis, University of Toulouse, 2008.

- [14] K. Kassmi, M. Hamlaoui and F. Olivier, Design and Modeling of a Photovoltaic System Adapted by an Analog MPPT Control, *Revue des Energies Renouvelables*, Vol. 10, No. 4 (2007), pp. 451-462.
- [15] T. Mrabti, M. El Ouariachi, K. Kassmi, F. Olivie and F. Bagui, Design, Modeling and Realization of a Medium-Power Photovoltaic System, *Revue des Energies Renouvelables*, Vol. 11, No. 4 (2008), pp. 567-575.
- [16] Belkaid Abdelhakim, Design and Implementation of a High-Performance MPPT Control for an Autonomous Photovoltaic Conversion Chain, Doctoral thesis, University of Ferhat Abbas - Setif 1, 2015.
- [17] A. Hania, Magister in Electrotechnics, Option: Mastery of Energies Intended for High-Power PV Systems, 2014.
- [18] Minwon Park and In-Keun Yu, Member IEEE, A Study on the Optimal Voltage for MPPT Obtained by Surface Temperature of Solar Cell, Changwon National University, South Korea, 2000.
- [19] S. Lalouni, Study, Control and Simulation of a Hybrid (Photovoltaic-Wind) Chain for Electrical Energy Production, Doctoral thesis, University of Bejaia, Algeria, 2009.
- [20] A. T. Singo, Photovoltaic Power Supply System with Hybrid Storage for Energy-Autonomous Housing, Doctoral thesis, Henri Poincare University, Nancy 1, France, 2010.
- [21] S. Belakehal, Design and Control of Permanent-Magnet Machines Dedicated to Renewable Energies, Doctoral thesis, University of Constantine, Algeria, 2010.
- [22] Z. Laid, Technical Study of an Off-Grid Photovoltaic-Wind Hybrid Energy System, Doctoral thesis, University of Constantine, Algeria, 2010.
- [23] F. Belhachat, Neuro-Fuzzy Control of an MPPT Chopper, Magister thesis, ENP, June 2007.
- [24] D. Djazira, Realization of a Battery Charger Based on Photovoltaic MPPT Control, Academic Master's thesis, June 2022.

[25] M. N. Mchalik and Ch. Hmada, Modeling and Simulation of a Photovoltaic System in Autonomous Operation and Connected to the Grid, Master's thesis, Kasdi University [remaining bibliographic information not visible in the provided image].

[26] Worku, M. Y., Hassan, M. A., Abido, M. A., & Alhems, L. M. (2023). *A Comprehensive Review of Recent Maximum Power Point Tracking Techniques for Photovoltaic Systems under Partial Shading*. **Sustainability**, **15**(14), 11132. <https://doi.org/10.3390/su151411132>