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Thesis

**Real-Time Implementation and Performance
Comparison of MPPT Techniques in a Photovoltaic
Energy Conversion System**

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

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All praise is due to Allah, Lord of the Worlds.

Dedication

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I dedicate the fruit of my efforts to my beloved parents, whose unwavering support, encouragement, and sacrifices have been the foundation of my academic journey. May Allah bless them and keep them as a source of pride and inspiration in my life.

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May this humble work be a source of benefit, and may Allah grant success and prosperity to all.

Abstract

This work presents the modeling, simulation, and real-time implementation of a photovoltaic (PV) energy conversion system incorporating a Boost DC-DC converter and advanced Maximum Power Point Tracking (MPPT) techniques. The main objective is to maximize the energy extracted from the photovoltaic generator while ensuring stable operation under varying environmental conditions, particularly fluctuations in solar irradiance and temperature. A comprehensive mathematical model of the PV module and the Boost converter was developed using the MATLAB/Simulink environment. Three MPPT algorithms were implemented and evaluated: the conventional Perturb and Observe (P&O) method, the Fuzzy Logic Controller (FLC), and the Particle Swarm Optimization (PSO) algorithm. To validate the simulation results, the developed control strategies were deployed in real time on a Texas Instruments TMS320F28379D (C2000) digital signal controller, which generated the pulse-width modulation (PWM) signals required for converter control. Simulation and experimental results demonstrated the effectiveness of all investigated MPPT techniques in tracking the maximum power point and improving the overall efficiency of the photovoltaic system. However, the intelligent approaches, particularly the PSO algorithm, exhibited superior performance in terms of tracking accuracy, response speed, stability, and oscillation reduction around the operating point. The FLC method also provided enhanced performance compared with the conventional P&O technique, especially under rapidly changing weather conditions.

Keywords: Photovoltaic System, MPPT, Perturb and Observe, Fuzzy Logic Control, Particle Swarm Optimization, TMS320F28379D.

Résumé

Ce travail présente la modélisation, la simulation et l'implémentation en temps réel d'un système de conversion d'énergie photovoltaïque (PV) intégrant un convertisseur Boost DC-DC et des techniques avancées de poursuite du point de puissance maximale (MPPT). L'objectif principal est de maximiser l'énergie extraite du générateur photovoltaïque tout en assurant un fonctionnement stable sous des conditions environnementales variables, notamment les fluctuations de l'irradiance solaire et de la température. Un modèle mathématique complet du module photovoltaïque et du convertisseur Boost a été développé à l'aide de l'environnement MATLAB/Simulink. Trois algorithmes MPPT ont été implémentés et évalués : la méthode conventionnelle Perturb and Observe (P&O), le contrôleur à logique floue (FLC) et l'algorithme d'optimisation par essaim de particules (PSO). Afin de valider les résultats de simulation, les stratégies de commande développées ont été déployées en temps réel sur un contrôleur numérique Texas Instruments TMS320F28379D (C2000), chargé de générer les signaux de modulation de largeur d'impulsion (PWM) nécessaires à la commande du convertisseur. Les résultats de simulation et expérimentaux ont démontré l'efficacité de toutes les techniques MPPT étudiées pour suivre le point de puissance maximale et améliorer le rendement global du système photovoltaïque. Toutefois, les approches intelligentes, en particulier l'algorithme PSO, ont présenté des performances supérieures en termes de précision de poursuite, de rapidité de réponse, de stabilité et de réduction des oscillations autour du point de fonctionnement. La méthode FLC a également offert de meilleures performances que la technique conventionnelle P&O, notamment sous des conditions météorologiques rapidement variables.

Mots-clés : Système photovoltaïque, MPPT, Perturb and Observe, Logique floue, Optimisation par essaim de particules, TMS320F28379D.

خلاصة

يقدم هذا العمل نمذجة ومحاكاة وتنفيذاً أنياً لنظام تحويل الطاقة الكهروضوئية (PV) المعتمد على محول رافع للجهد (Boost DC-DC Converter) وتقنيات متقدمة لتتبع نقطة القدرة العظمى (MPPT). ويتمثل الهدف الرئيسي في تعظيم الطاقة المستخرجة من المولد الكهروضوئي مع ضمان تشغيل مستقر في ظل الظروف البيئية المتغيرة، وخاصة تغيرات الإشعاع الشمسي ودرجة الحرارة. تم تطوير نموذج رياضي متكامل للوحدة الكهروضوئية وللمحول الرفع باستخدام بيئة MATLAB/Simulink. كما تم تنفيذ وتقييم ثلاث خوارزميات لتتبع نقطة القدرة العظمى، وهي: طريقة الاضطراب والملاحظة (P&O)، والمتحكم بالمنطق الضبابي (FLC)، وخوارزمية تحسين سرب الجسيمات (PSO). وللتحقق من نتائج المحاكاة، تم تطبيق استراتيجيات التحكم المقترحة في الزمن الحقيقي على المتحكم الرقمي TMS320F28379D (C2000) من شركة Texas Instruments، والذي تولى توليد إشارات تعديل عرض النبضة (PWM) اللازمة للتحكم في المحول. أظهرت نتائج المحاكاة والتجارب العملية فعالية جميع تقنيات MPPT المدروسة في تتبع نقطة القدرة العظمى وتحسين الكفاءة العامة للنظام الكهروضوئي. ومع ذلك، أظهرت الطرق الذكية، وخاصة خوارزمية PSO، أداءً متفوقاً من حيث دقة التتبع، وسرعة الاستجابة، والاستقرار، وتقليل التذبذبات حول نقطة التشغيل. كما قدمت طريقة المنطق الضبابي أداءً أفضل مقارنة بالطريقة التقليدية P&O، خاصة في ظل التغيرات السريعة في الظروف المناخية.

الكلمات المفتاحية: النظام الكهروضوئي، تتبع نقطة القدرة العظمى (MPPT)، الاضطراب والملاحظة (P&O)، المنطق الضبابي (FLC)، تحسين سرب الجسيمات (PSO)، TMS320F28379D.

List of descriptions

AC : Alternating Current

DC : Direct Current

FF : Fill Factor

FLC : Fuzzy Logic Controller

PVG: Photovoltaic Generator

I–V : Current–Voltage Characteristic

P–V : Power–Voltage Characteristic

IGBT : Insulated Gate Bipolar Transistor

I_{ph} : Photocurrent

I_L : Inductor Current

I_s : Output Current of the Converter

I_{sc} (I_{cc}) : Short-Circuit Current

I_{rs} : Reverse Saturation Current

MPPT : Maximum Power Point Tracking

MOSFET : Metal Oxide Semiconductor Field Effect Transistor

N_s : Number of Cells Connected in Series

N_p : Number of Cells Connected in Parallel

P&O : Perturb and Observe

PSO : Particle Swarm Optimization

PWM : Pulse Width Modulation

PV : Photovoltaic

R : Resistive Load

R_s : Series Resistance

Rsh : Shunt Resistance

SDM : Single Diode Model

STC : Standard Test Conditions

Tref:temperature reference

T : Cell Temperature

TL081 : Operational Amplifier Integrated Circuit

Voc (Vco) : Open-Circuit Voltage

Vmp : Voltage at Maximum Power

Imp : Current at Maximum Power

Ve : Input Voltage

Vs : Output Voltage

η : Conversion Efficiency

α : Duty Cycle

E : Solar Irradiance

G : Solar Irradiance / Junction Temperature (according to context)

k : Boltzmann Constant

q : Electron Charge

TMS320F28379D : Texas Instruments Digital Signal Controller

LA-25-NP : Current Sensor Model

LV-28-P : Voltage Sensor Model

Pmax : Maximum Power

Si : Silicon.

Mono-Si : Monocrystalline Silicon

Poly-Si : Polycrystalline Silicon

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GENERALE

INTRODUCTION

GENERALE INTRODUCTION

In recent years, global interest in renewable energy sources has increased due to the continuous rise in electrical energy demand, in addition to the environmental problems caused by fossil fuels such as pollution and global warming. Among the most important renewable energy sources is solar energy, which is considered a clean and widely available source. Solar radiation is converted into electrical energy using photovoltaic (PV) systems.

Photovoltaic systems are characterized by easy installation and low maintenance costs. However, their efficiency is directly affected by climatic conditions such as solar irradiance and temperature, which leads to continuous changes in the Maximum Power Point (MPP). For this reason, Maximum Power Point Tracking (MPPT) techniques have been developed to extract the maximum possible power from photovoltaic panels and improve the overall efficiency of the system [1].

The main problem addressed in this study lies in improving the performance of the photovoltaic system and ensuring fast and accurate tracking of the Maximum Power Point under changing climatic conditions, while reducing oscillations and power losses that affect the system efficiency. This study also raises an important question regarding the effectiveness of different control algorithms, such as P&O, FLC, and PSO, in achieving the best possible performance in terms of speed, stability, and efficiency [2].

The objective of this work is to model and simulate a photovoltaic (PV) energy conversion system using MATLAB/Simulink and to investigate the performance of a Boost DC-DC converter interfaced with the PV generator. Furthermore, three Maximum Power Point Tracking (MPPT) techniques, namely Perturb and Observe (P&O), Fuzzy Logic Control (FLC), and Particle Swarm Optimization (PSO), are implemented and comparatively evaluated. The study aims to assess the dynamic response, tracking accuracy, stability, and efficiency of these algorithms under varying irradiance and temperature conditions in order to identify the most effective MPPT strategy. In addition to simulation-based analysis, the selected MPPT techniques are implemented in real time on a Texas Instruments C2000 digital signal controller to validate their practical feasibility and performance in an embedded photovoltaic system [3].

This paper is organized as follows. Section 1 presents the fundamentals of photovoltaic systems. Section 2 describes the modeling and simulation of the proposed photovoltaic system. Section 3 details the real-time implementation using a Texas Instruments C2000 controller and discusses the experimental results.

CHAPTER I

FUNDAMENTALS

OF

PHOTOVOLTAIC

SYSTEMS

I.1 .INTRODUCTION

Solar photovoltaic (PV) energy is electrical energy produced through the direct conversion of solar radiation using semiconductor materials such as silicon. This process is based on the photoelectric effect, where photons of light release electrons inside the solar cell, generating an electric current. Because a single cell produces a limited power, several cells are connected to form a solar panel, and several panels can be assembled to form an integrated photovoltaic system. This chapter deals with the basics of photovoltaic systems in terms of structure, components, and types, in addition to explaining the principle of solar cell work and the uses of these systems in the production of electrical energy for residential, industrial and independent systems.

I.2. Renewable energies

Renewable energies are energy resources that are naturally replenished and available in unlimited quantities, such as solar, wind, hydro, biomass, and geothermal energy. These sources provide clean and sustainable alternatives to conventional fossil fuels and play a crucial role in meeting the world's growing energy demand while reducing environmental pollution [4] .

I.3 Solar energy source

Solar energy comes from nuclear fusion which takes place at the center of the sun, it is composed of 75% hydrogen, 23% helium and 2% other molecules. Hydrogen atoms are converted to helium by a large-scale thermonuclear fusion reaction. In addition, according to Einstein's formula $E = mc^2$, mass is converted into energy. This reaction keeps the surface of the sun at a temperature of about 5800 ° K. The sun's energy is uniformly converted into radiation in all directions of space. When it traveled 150 million kilometers from the sun to the earth, its total alien density dropped to 1367/m². This value is called the solar constant. In one hour, the energy that the earth draws from the sun is 1.2×10^{17} , which is enough to sustain itself for nearly a year. Photovoltaic panels can use this free energy by converting it into electricity [5] .

I.3.1. Solar radiation in space

The Sun is a massive star with a diameter of about 1.39 million kilometers, approximately 50 times larger than the Earth's diameter. It is composed mainly of 80% hydrogen and 19% helium, with a small percentage of other chemical elements.

The Sun generates its energy through nuclear fusion reactions in its core, where approximately 564 million tons of hydrogen are converted into 560 million tons of helium every second at a temperature of about 25 million degrees Celsius. As a result, nearly 4 million tons of mass are transformed into radiant energy and released into space each second [6] .

Main characteristics of solar radiation:

- Light travels at a speed of 300,000 km/s.
- Sunlight takes about 8 minutes to reach the Earth.
- The average distance between the Sun and the Earth is approximately 150 million kilometers [7] .
- The solar spectral distribution reaches its maximum at a wavelength of about 0.5 μm (micrometers).
- The Sun's surface temperature, considered as a black body, is approximately 5780 K.
- Diameter of the Sun: 1.39×10^9 m.
- Diameter of the Earth: 1.27×10^7 m.

I.3.2. Solar radiation

Our sun is a dwarf star, composed of 74% hydrogen and 25% helium and for some heavier elements, the surface temperature is about 5530 [8].

I.3.2.1. Direct radiation

Direct radiation is the difference between global radiation and radiation diffuse. [8].

I.3.2.2. Diffuse radiation

This is due to the absorption and scattering of part of the global solar radiation by the atmosphere and its reflection by clouds and aerosols [8].

I.3.2.3. Reflected radiation or soil albedo

It is the radiation that is reflected from the ground or from objects in its vicinity. surface. This albedo can be important when the soil is particularly reflective (water, snow, etc....) [8].

I.3.2.4. Global influence

Global radiation is subdivided into direct, diffuse and reflected radiation soil). In the figure below, all the solar radiation received is schematized on a land surface

Weather stations typically measure horizontal global radiation by a pyranometer placed horizontally at the required location [8].

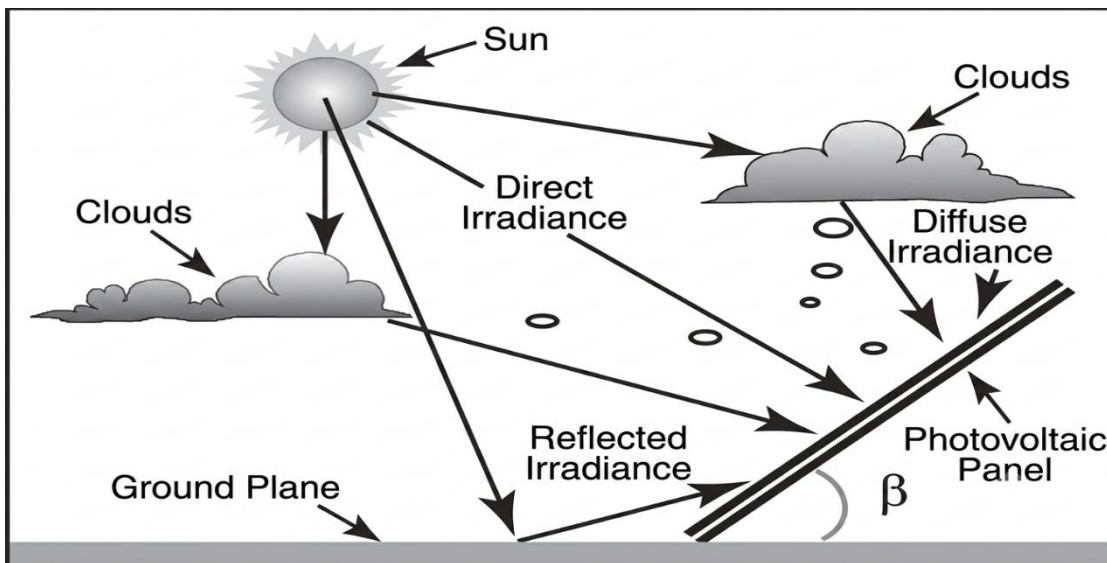


Figure .I.1: Component of global radiation on a horizontal plane

I.3.3. The solar spectrum

The sun emits energy in the form of electromagnetic radiation, which together forms solar radiation; measured in (W/m^2) and presents the power per unit area [9] .

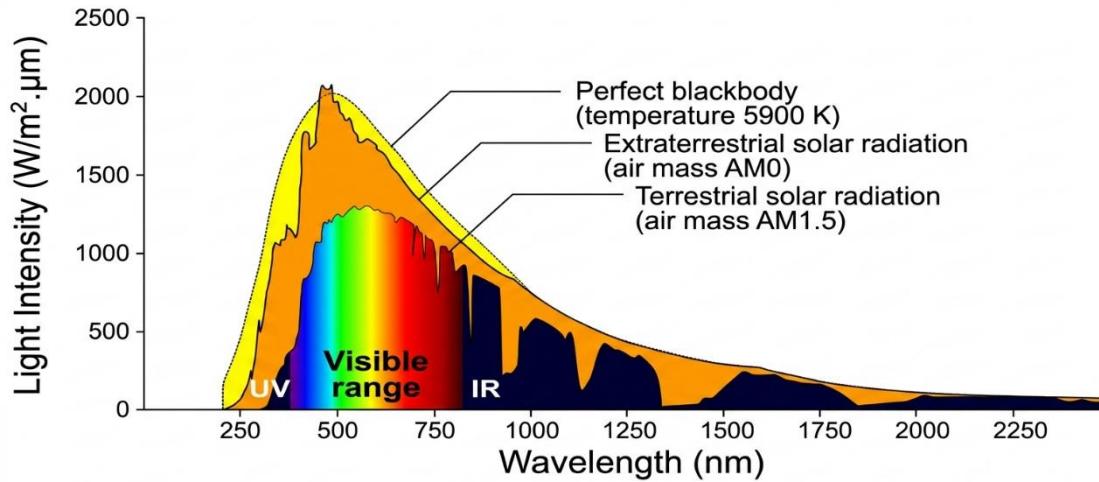


Figure I.2: Light output per unit area

I.3.4. Solar energy

The solar constant is the density of solar energy that reaches the outer boundary of the atmosphere facing the sun. The value of the illuminance is commonly taken to be 1360 W/m^2 . At ground level, the solar energy density is reduced to 1000 W/m^2 due to absorption in the atmosphere [10].

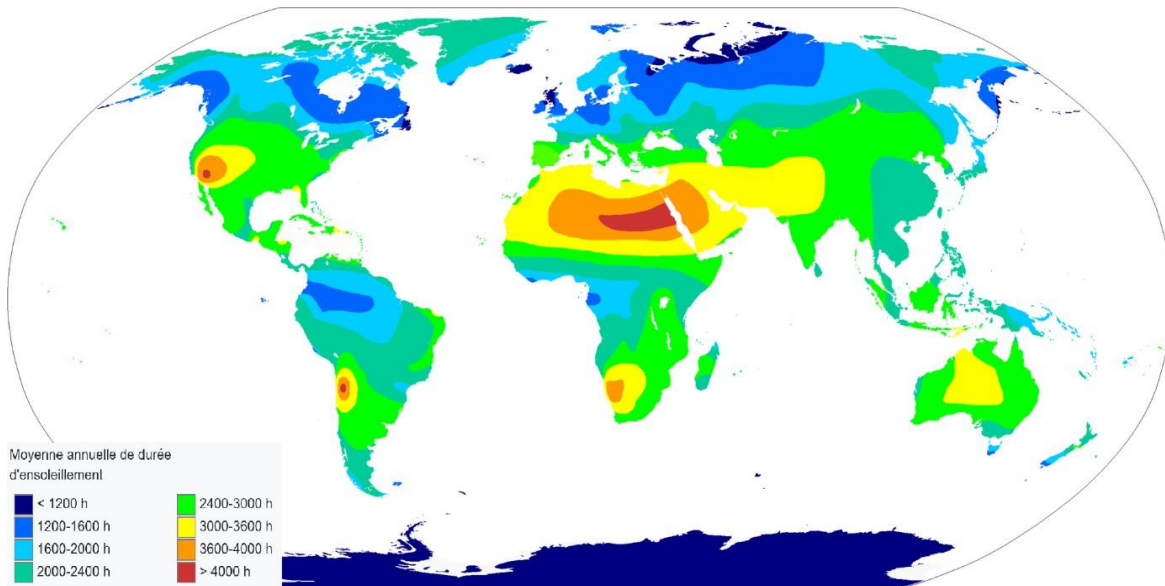


Figure I.3: shows the different values of illuminance in the world.

Albert Einstein, through his work on the photoelectric effect, demonstrated that light has not only a wave nature but also a particle nature. The energy of light is carried by particles called photons. The energy of a photon is given by:

$$E = h\nu = \frac{hc}{\lambda} \quad (I.1)$$

Where:

E: photon energy (J)

h: Plancks constant (J·s)

c: speed of light (m/s)

λ : wavelength (m)

ν : frequency (s^{-1})

A convenient expression for photon energy is

$$E = \frac{1.25}{\lambda} \quad (I.2)$$

Thus, the shorter the wavelength, the greater the photon energy [11] .

The Sun emits electromagnetic radiation over a wavelength range from approximately 0.22 μm to 10 μm . The solar energy distribution is approximately:

- 9% in the ultraviolet (UV) region ($\lambda < 0.4 \mu\text{m}$).
- 47% in the visible region (0.4–0.8 μm).
- 44% in the infrared (IR) region ($\lambda > 0.8 \mu\text{m}$).

1. 4. Photovoltaic system

A Photovoltaic (PV) system is a renewable energy conversion system that directly transforms solar radiation into electrical energy through the photovoltaic effect. This phenomenon occurs when sunlight interacts with semiconductor materials, generating an electric current. Unlike conventional power generation technologies, PV systems operate without moving parts, fuel consumption, or harmful emissions, making them a clean and reliable energy source. A typical PV system consists of photovoltaic modules and power

conditioning devices that ensure efficient energy conversion and delivery to electrical loads under varying environmental conditions [12][13] .

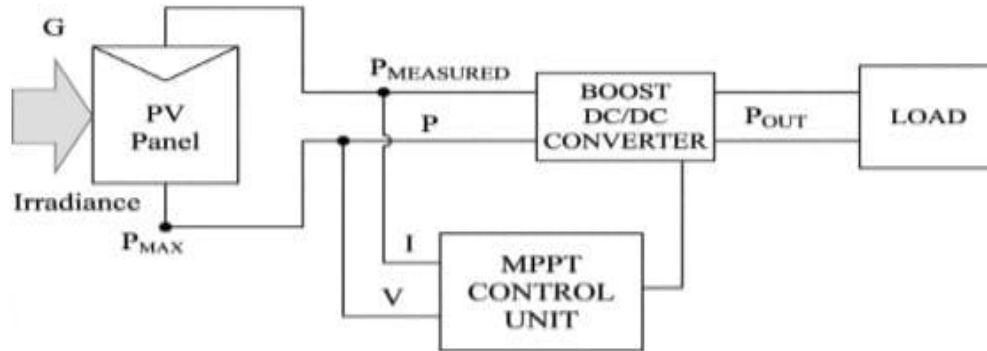


Figure .I.4: block diagram of the hybrid system

1 .5. Photovoltaic Panel

Crystalline silicon solar cells are the fundamental pillar of renewable energy technology. Their superiority is attributed to the unique atomic structure of silicon, as its atoms are organized in a tight covalent lattice that provides an ideal path for electron movement when light photons are absorbed. These cells vary between monocrystalline (Mono-Si), which often appear with rounded or cropped corners as a result of being manufactured from cylindrical ingots, and polycrystalline (Poly-Si), which take a full square shape for ease of stacking and manufacturing. Despite the emergence of alternative technologies, silicon remains the primary choice globally due to its great abundance in the Earth's crust, its chemical stability which ensures a long operational life, and its high ability to achieve an ideal balance between production cost and energy conversion efficiency [14].

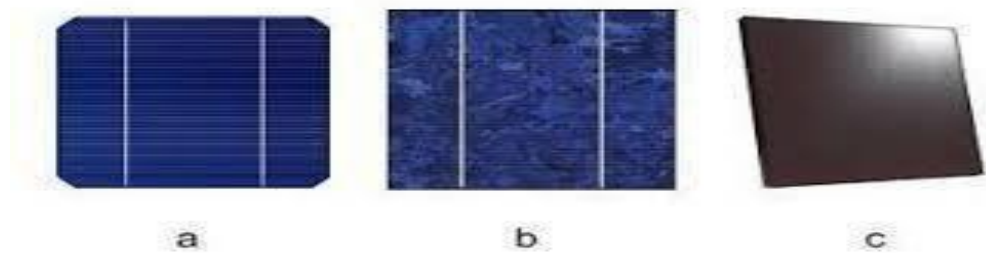


Figure .I.5: Different types of silicon solar cells: (a) Monocrystalline, (b) Polycrystalline, (c) Amorphous.

I.5 1. The Photovoltaic Cell

A photovoltaic cell is an electronic component which, when exposed to light (photons), generates a voltage. The resulting current is a direct current (DC); the semiconductors that constitute photovoltaic cells are based on silicon (Si), cadmium sulfide (CdS), or cadmium telluride (CdTe). They appear in the form of two thin plates in close contact. This semiconductor is sandwiched between two metal electrodes, and the entire assembly is protected by glass [15] .

I.5.2. Operation of the Photovoltaic Cell

In fact, the photocell is composed of semiconductor materials doped P (lack of electrons) and N (excess of electrons), where the P-N type junction allows the excess electrons from the N zone to cross the junction and occupy the holes in the P zone. Thus, when light strikes the surface (N-doped) of a photovoltaic cell, the photons constituting this light communicate their energy to the atoms of the material, releasing electrons from the atoms, which thus generate N charges (electrons) and P charges (holes) [15] .

Now, the displacement of electrons (created by the energy of photons) is synonymous with the production of electricity. For a photocell, the production of electricity is linked to the production of electrons (and holes) by the photons of light illuminating the device. The more photons strike the cell, the greater the quantity of electricity produced. For a given irradiance, this quantity depends on the conversion efficiency of the photocell (produced energy / received energy) [15].

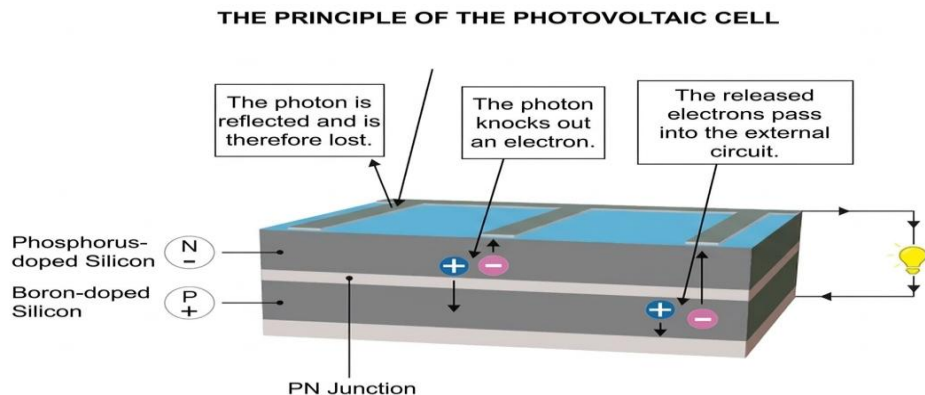


Figure .I.6: Working principle of a PV cell

I.5 .2.1 Materials Used in PV Cells

Silicon is currently the most widely used material for manufacturing photovoltaic cells due to its abundance, stability, and well-established technology. It offers good electrical properties and high efficiency in converting solar energy into electricity. Moreover, silicon-based solar cells have proven reliability and a long operational lifespan, making them suitable for both residential and industrial applications [16].

I.5.2.2. The monocrystalline silicon photovoltaic cell

Monocrystalline solar panels are widely used to power homes and public grids. Monocrystalline silicon is obtained by cooling molten silicon to form a uniform crystal. These solar panels have a distinctive blue color and excellent efficiency in converting sunlight into electricity. As shown in Figure I.6 [17].

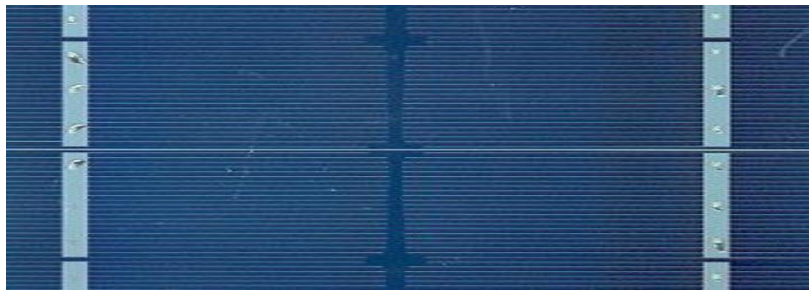


Figure .I.7: Monocrystalline cells

I.5.2.3. The polycrystalline silicon photovoltaic cell

It can be easily recognized by its blue crystals, and the photovoltaic cell consists of a square-shaped silicon wafer. This type of photovoltaic cell is generally found in domestic, agricultural, or industrial installations. As shown in Figure I.7 [18].

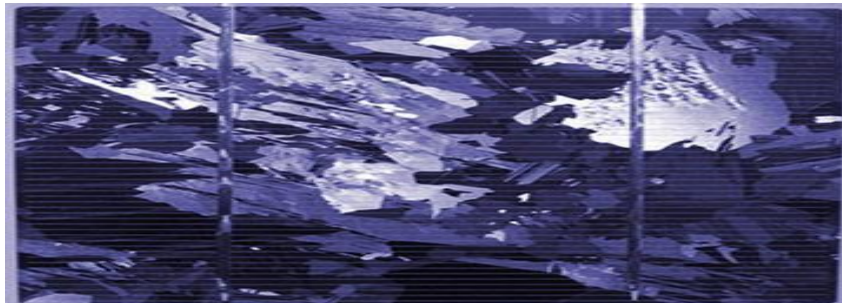


Figure .I.8: Polycrystalline cells

I.5 .2. 4.The amorphous silicon cell

The amorphous photovoltaic cell is composed of a thin layer of silicon. This type of photovoltaic cell is used in public lighting and solar calculators. Amorphous silicon is obtained by means of silicon gas, and this gas is evaporated onto soil, glass, or a supporting metal, and the color of this photovoltaic cell is dark gray. As shown in Figure I.8 [19].

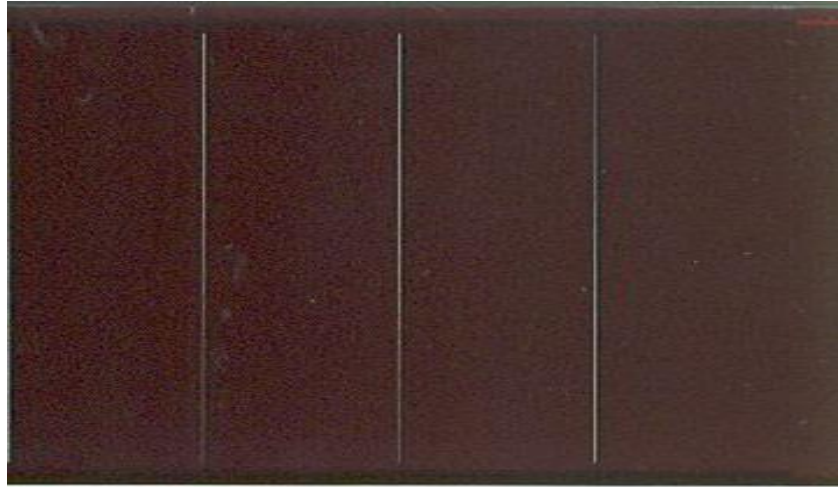


Figure. I. 9: Amorphous Photovoltaic Cell

I.6. Photovoltaic modules

Photovoltaic modules are a group of photovoltaic cells connected to each other, which are assembled in series or parallel in order to generate more power according to the needs of the target applications.

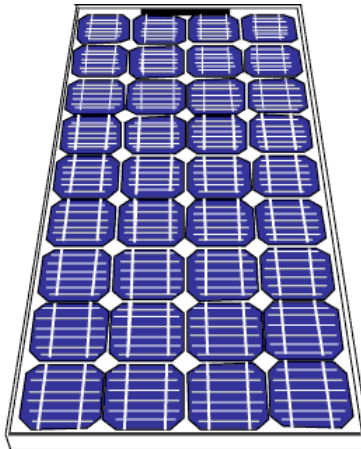


Figure .I.10: Photovoltaic Module

I.6. 1 Association in series

The association of photovoltaic cells in series makes it possible to obtain an output voltage equal to the sum of the voltages of all the cells, while the current flowing through them is the same (Figure I.11).

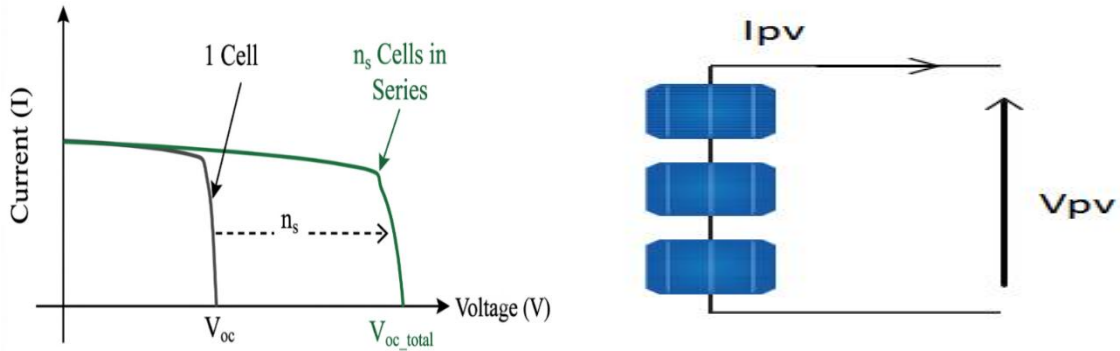


Figure .I.11: Association of cells in series.

$$I_{pv} = I_{ph} - I_{s1} \left(e^{\frac{q(V_{pv} + I_{pv}N_sR_s)}{m_1kT}} - 1 \right) - I_{s2} \left(e^{\frac{q(V_{pv} + I_{pv}N_sR_s)}{m_2kT}} - 1 \right) - \frac{V_{pv} + I_{pv}N_sR_s}{R_p} \quad (I.3)$$

I.6.2 Parallel association

The parallel grouping of the cells makes it possible to flow a current equal to the sum of the currents supplied by all the cells, while the voltage across the cells remains the same (Figure I.12) [20].

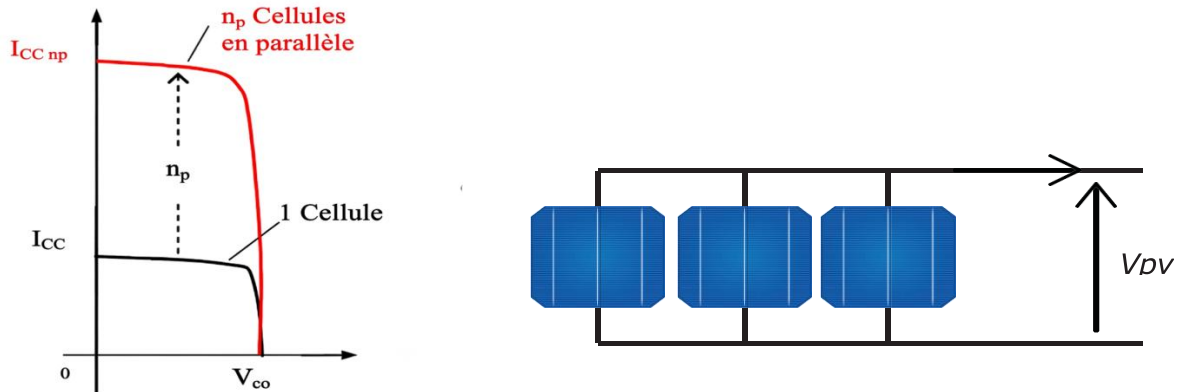


Figure .I.12: Connection of cells in parallel

The maximum current will become:

$$I_{cc}, N_p = N_p \times I_{cc} \quad (I.4)$$

I.6.3 The photovoltaic field

To provide the voltage and current necessary for the installation, the photo-voltaic field generally consists of many modules, composed of several photovoltaic cells, connected in series and in parallel (Figure I.13)[21] [22].

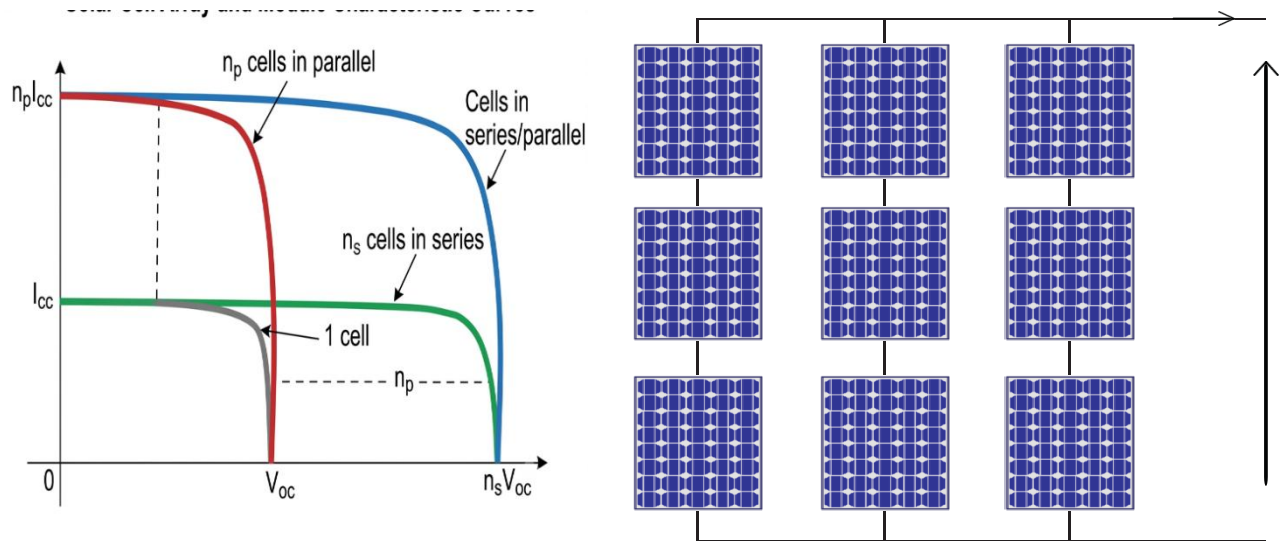


Figure .I.13:Combination of modules and in series and in parallel.

I .7. DC-DC Power Converters (Choppers)

A chopper is a DC/DC converter used to convert direct current energy from a given voltage (or current) level into direct current energy at another voltage (or current) level.

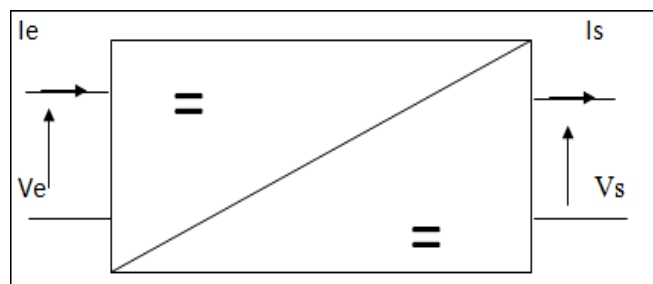


Figure. I.14: DC-DC Step-up Converter

I.7.1. Buck Converter (Step-down chopper)

The relationship between the input voltage (V_i) and output voltage (V_o) is determined by the duty cycle (α) as follows: Where α in $[0, 1]$. This topology is strictly used for stepping down the voltage [23] .

$$V_o = \alpha \cdot V_i \quad (I.5)$$

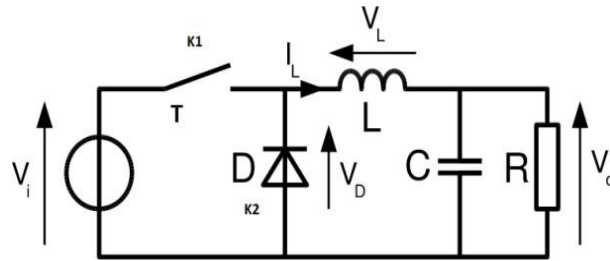


Figure .I.15: Buck converter circuit diagram

The switch K1 is closed during a fraction of the switching period (T). The input source supplies energy to the load (R) through the inductor (L).

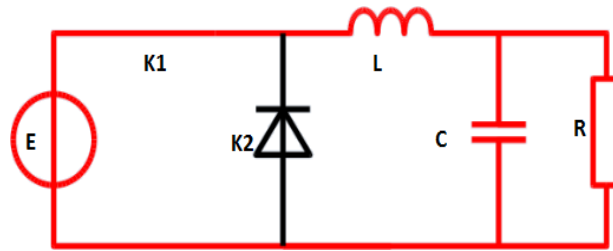


Figure .I.16: Equivalent circuit when K1 is closed

When the transistor turns off, the diode ($K2$) ensures the continuity of the inductor current. The energy stored in this inductor is then discharged into the capacitor and the load resistor[24].

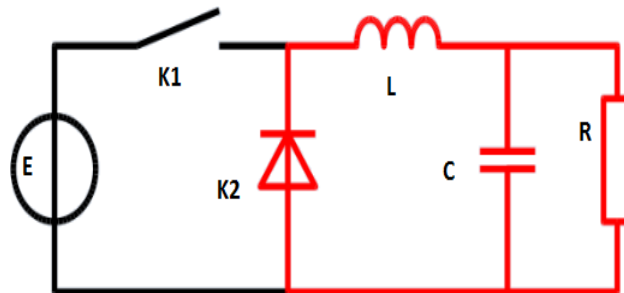


Figure .I.17: Equivalent circuit when K1 is open.

I.7. 2.Parallel Chopper (BOOST)

The mathematical expression governing the step-up behavior of the Boost converter is given by:

$$V_o = \left\{ \frac{1}{1 - \alpha} \right\} \cdot V_i \quad (I.6)$$

Due to this relationship, the output voltage is always higher than or equal to the input voltage.2.6[25].

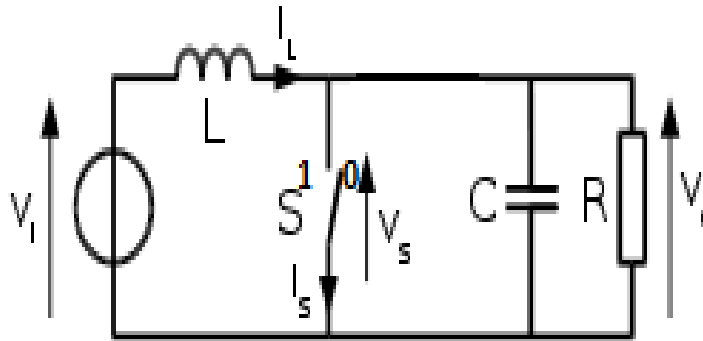


Figure. I.18: circuit diagram Boost converter

This chopper consists of three components: an inductor (L), a capacitor (C), and a switch (S) that can take two states: 1 and 0.

-Operation:

The operating principle of this type of chopper can be explained as follows:

When the switch is in position 1, the circuit is divided into two parts: on the left, the source charges the inductor; meanwhile, on the right, the capacitor maintains the output voltage using previously stored energy [26] .

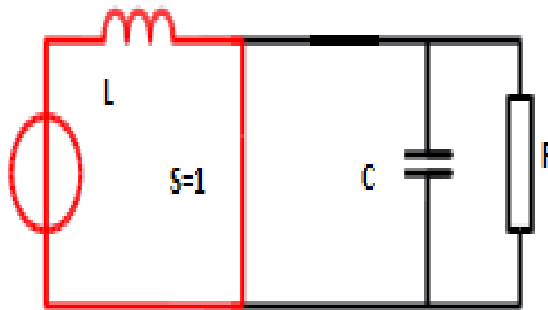


Figure .I.19: Equivalent circuit when S=1

When the switch changes to position 0 (OFF), the DC source and the energy stored in the inductor together supply the right-side circuit, resulting in an increase in the output voltage.

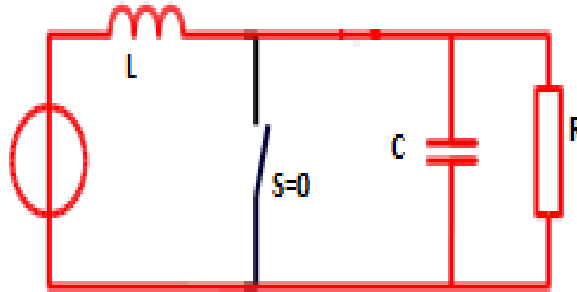


Figure I.20: Equivalent circuit when $S=0$

I.7.3. Buck-Boost Converter

The buck-boost converter is a switching power supply that converts one DC voltage into another DC voltage of lower .

$$V_o = -\left\{\frac{\alpha}{1-\alpha}\right\} \cdot V_i \quad (I.7)$$

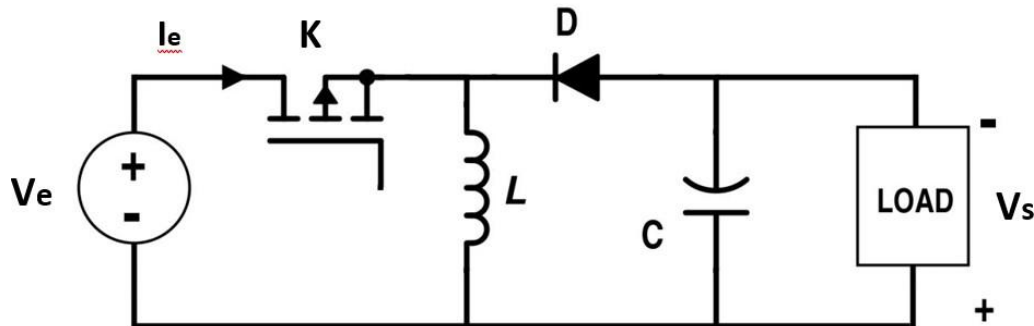


Figure I.21: Buck-boost converter diagram

or larger value, but of reverse polarity. The schematic diagram of a buck-boost converter is shown in Figure I-22 [27].

This converter has two operating phases:

-Phase 1 (K closed): the switch K is conductive during the time αT , the energy is stored in L and the output voltage is negative with respect to the common point: the diode D is then blocked.

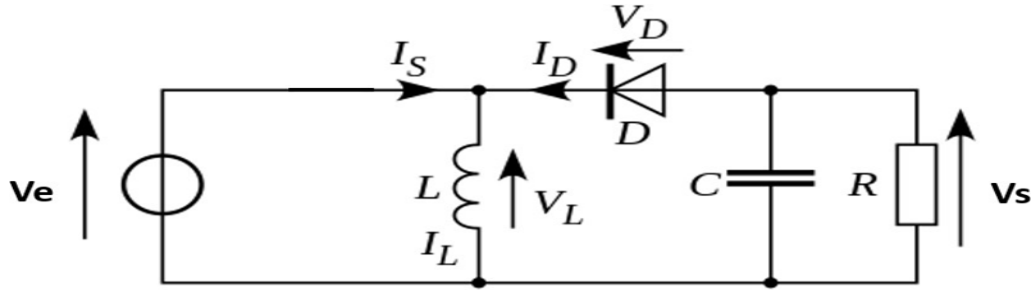


Figure .I.22:Equivalent Circuit for Phase 2

Phase 2 (K open): Blocking the switch K causes the inductor to discharge in the load R and capacitor C. This discharge can be total or partial [22] .

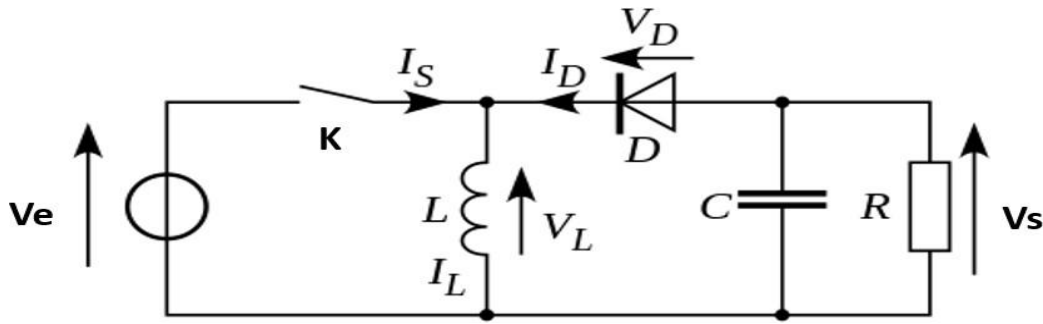


Figure .I.23: Equivalent Circuit for Phase 2

I.8. Classifications of Photovoltaic Systems

I.8.1. Autonomous (Stand-Alone) Systems

Stand-alone PV systems operate independently of the main electrical grid. They are highly utilized in remote, rural, or isolated areas where grid extension is physically or economically impractical. These systems typically require energy storage (such as batteries) to bridge the gap between energy production during the day and consumption at night or during cloudy periods [26] .

I.8.2. DC Loads

DC loads refer to electrical devices that operate directly on direct current (DC) power without requiring conversion. In PV systems, these loads (such as LED lighting, DC water pumps, or specific telecommunication equipment) can be connected directly to the output of the DC-DC converter, minimizing energy conversion losses [27] .

I.8.3. AC Loads

AC loads represent standard household and industrial appliances that operate on alternating current (AC), such as refrigerators, televisions, and air conditioners. To power these loads from a PV system, a power inverter must be integrated to convert the system's DC voltage into stable AC voltage (e.g., 230V, 50Hz) [28] .

I.8.4. Grid-Connected Photovoltaic Systems

Grid-connected PV systems are integrated directly into the local electrical utility network. Unlike autonomous systems, they do not strictly require battery storage. When the PV system generates more electricity than local loads consume, the excess power is injected into the public grid. Conversely, during low solar irradiance, the grid supplements the power shortage [29] .

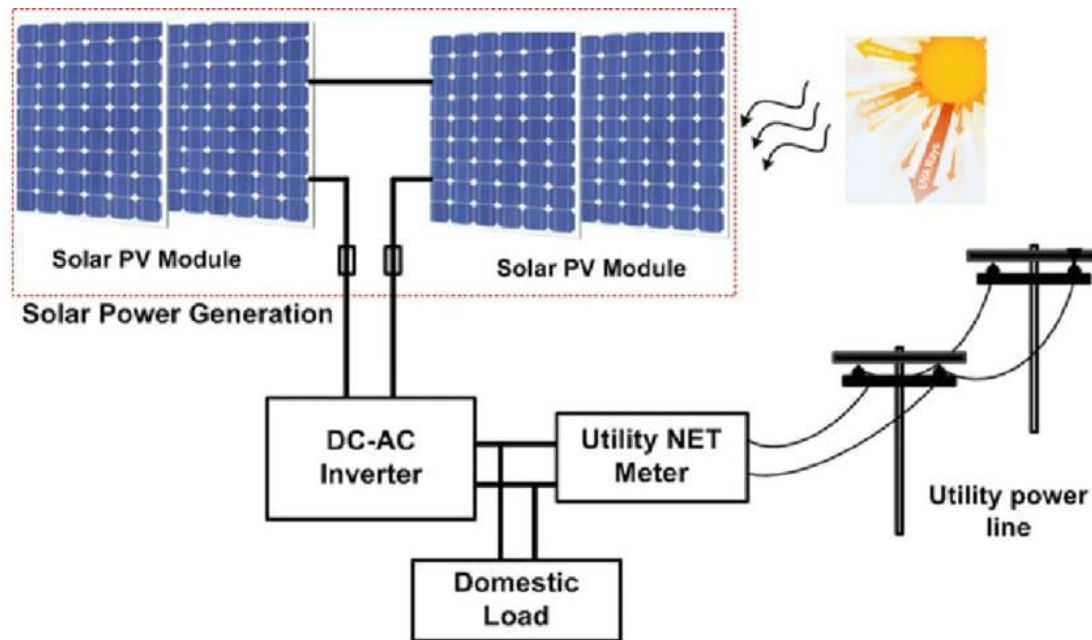


Figure .I.24:Grid-Connected Photovoltaic Systems

I.9. Conclusion

In this chapter, the fundamental concepts of photovoltaic (PV) systems were reviewed. The operating principle of the PV cell based on the P–N junction was discussed, along with the characteristics of the main photovoltaic technologies, namely

monocrystalline, polycrystalline, and amorphous silicon. Furthermore, the operating principles of the most commonly used DC–DC converter topologies, including Buck, Boost, and Buck–Boost converters, were presented and analyzed. Finally, photovoltaic systems were classified into standalone and grid-connected configurations according to their application and load requirements. The theoretical foundations established in this chapter provide the necessary background for the development and implementation of advanced MPPT techniques and power management strategies presented in the following chapter.

CHAPTER II

MODELLING

OF SYSTEM

PHOTOVOLTAICS

II.1 . Introduction

This chapter aims to study the mathematical modeling of a photovoltaic generator based on a single-diode model, analyzing its electrical properties under the influence of solar radiation and temperature change. It also deals with the design and simulation of three algorithms for tracking the maximum power point (MPPT), namely P&O, FLC, and PSO, and comparing them in terms of tracking speed, accuracy, oscillation, and computational complexity, with the aim of determining the most efficient algorithm to improve the performance of photovoltaic systems .

II.2. Modeling of the photovoltaic system

II.2.1. Modeling of a photovoltaic cell

The model you are describing is commonly known as the Single-Diode Model (SDM) of a photovoltaic cell. By introducing R_s and R_{sh} , the model moves from an ideal representation to a practical or empirical one that accounts for real-world energy losses [30] .

A series resistor (R_s) Represents the internal ohmic losses in the cell due to the strength of semiconductor materials and metal contacts.

A shunt resistor (R_{sh}) Models stray current leakage in the cell.

A parallel diode that models the PN junction.

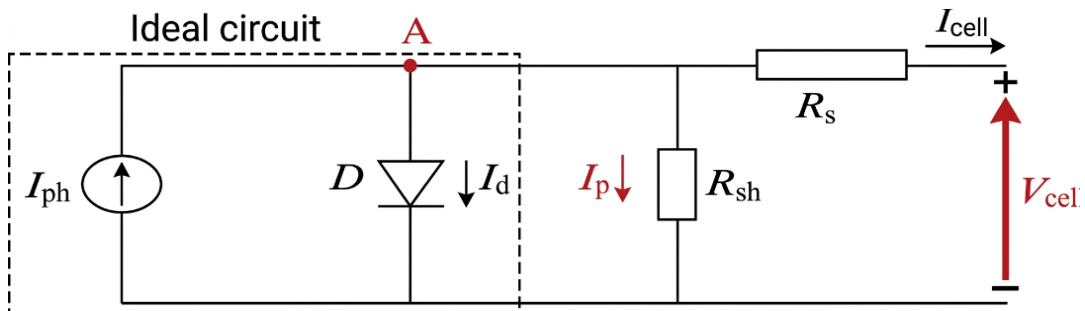


Figure. II.1: Electrical diagram of a photovoltaic cell

The selection of the model depends on the required balance between simplicity and accuracy, with the five-parameter model offering a good compromise. These models are used to describe the electrical I–V characteristics of photovoltaic cells and modules and to derive the load current equation Kirchhoff's law. allows us to write the following relation.

$$I_{ph} = I_{cel} + I_d + I_{rs} \quad (II.1)$$

$$I_{cel} = I_{ph} - I_d - I_{rs} \quad (II.2)$$

By substituting the expressions of the diode current and the shunt current into the main current equation, the complete nonlinear model of the photovoltaic cell becomes

$$I_{cell} = I_{ph} - I_{rs} \cdot \left(e^{\frac{V_{cell} + R_s \cdot I_{cell}}{V_{th}}} - 1 \right) - \frac{V_{cell} + R_s \cdot I_{cell}}{R_{sh}} \quad (II.3)$$

The diode current is described by the Shockley diode equation, which models the nonlinear behavior of the semiconductor junction [31].

$$I_d = I_{rs} \cdot \left(e^{\frac{V_d}{V_{th}}} - 1 \right) \quad (II.4)$$

The voltage across the diode is equal to the output voltage of the cell plus the voltage drop across the series resistance

$$V_d = V_{cell} + R_s \cdot I_{cell} \quad (II.5)$$

The thermal voltage depends on the cell temperature and physical constants of the semiconductor material. It is given by

$$V_t = \frac{n \cdot k \cdot T}{q} \quad (II.6)$$

$$q = 1.602 \times 10^{-19} \text{ C}$$

$$k = 1.381 \times 10^{-23} \text{ J/K}$$

II.2.1. 1. The photo-current I_{ph}

It is the current generated by a cell, it is proportional to the solar irradiation and is slightly influenced by the temperature according to the following equation [32].

With:

$$I_{ph} = I_{sc} - K_i \cdot (T - T_{ref}) \frac{G}{1000} \quad (II.7)$$

II.2.1. 2. The saturation current I_0

This current varies with temperature and is given p

$$I_0 = I_{rs} \cdot \left(\frac{T}{T_{ref}} \right)^3 \cdot e^{\frac{q \cdot E_{g0} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T} \right)}{n \cdot k}} \quad (II.8)$$

II.2.1. 3. The diode's reverse saturation current (leakage current) I_{rs}

Its expression is given by the equation

$$I_{rs} = \frac{I_{sc}}{e^{\frac{V_{oc}}{n \cdot V_{th}}} - 1} \quad (II. 9)$$

II.2.1. 4. The shunt resistance current

$$I_{sh} = \frac{V + I R_s}{R_{sh}} \quad (II. 10)$$

II.2.1.5. The current of the panel

The equations described above cannot represent the I-V characteristic of a PV Module since they are specific to a single PV cell which represents the basic element of the panel, so we introduce the equation specific to a module

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot k \cdot N_s \cdot T} \right) - 1 \right] - I_{sh} \quad (II. 11)$$

II.3.2 .Key parameters of the panel**II.3.2.1. Open Circuit Voltage (V_{oc})**

This is the maximum voltage a cell can generate when not connected to any external load. This value depends on the characteristics of the p-n junction and the level of solar irradiation received [33].

II.3.2.2. Short-Circuit Current (I_{cc})

This represents the maximum current produced when the cell terminals are connected to each other. It depends mainly on the light intensity and properties of the semiconductor material

II.3.2.3. Maximum Power (P_m)

This is the maximum electrical power that the cell can deliver under specific conditions, usually under standard test conditions (STCs). Expressed in watts (W), it reflects the overall conversion efficiency of the cell [34].

$$P_m = V_{mp} \times I_{mp} \quad (II. 12)$$

II.3.2.4 . Conversion efficiency (η)

This is the ratio of the maximum electrical power produced to the total solar power received on the surface of the cell. It is expressed as a percentage and indicates the cell's ability to convert energy

$$\eta = \frac{P_m}{P_{in}} = \frac{V_{mp} \times I_{mp}}{G \times A} \times 100\% \quad (\text{II. 13})$$

II.3.2.5. Form Factor (FF)

The form factor is a measure of the 'rectangularity' of the I-V curve. It corresponds to the ratio between the actual maximum power and the theoretical power that would be obtained if the I-V curve were perfectly rectangular[35].

$$FF = \frac{P_m}{V_{oc} \times I_{sc}} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (\text{II. 14})$$

This table presents the electrical characteristics of the photovoltaic module used in this study under standard test conditions (STC).

Table II.1: Electrical Characteristic of PV module under Standard Conditions<CST> T=25°C, G=1000W/m².

Rated power	200 W
Voltage at maximum power	33.45 V
Current at maximum power	6.05 A
Open Circuit Voltage	42.45 V
Short Circuit Current	6.53 A
Number of cells in series	Ns 72
Number of cells in parallel	Np 1

II.4. Simulation of photovoltaic panel using Matlab-Simulink

The photovoltaic (PV) panel is represented by a mathematical model based on electrical equations, where the current I is considered the input variable and the voltage V is obtained as the output. The simulation of the PV panel using MATLAB simulation software is As shown in the figure (II.2)

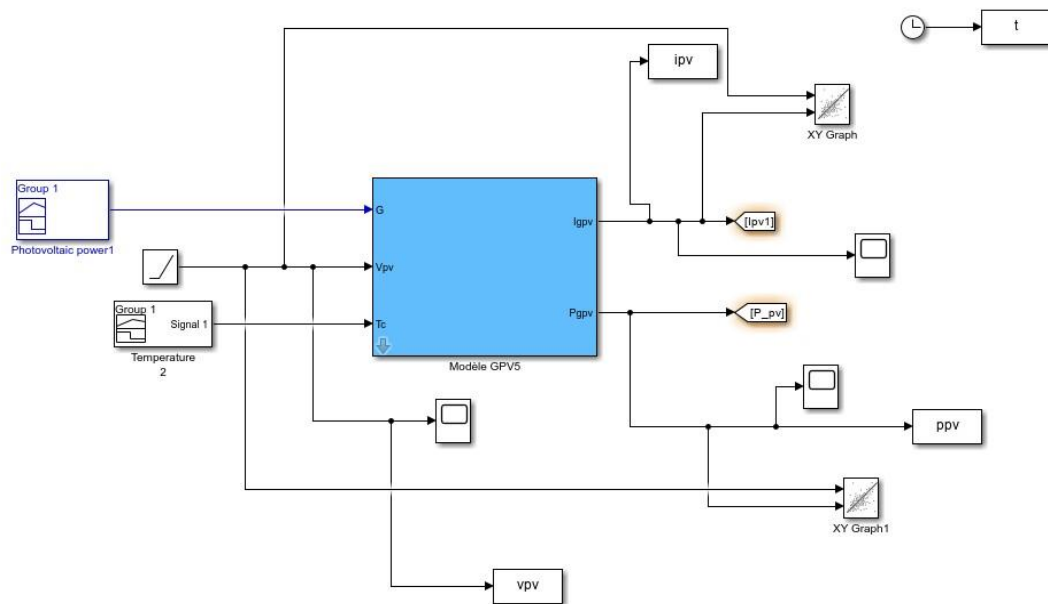


Figure. II.2: Simulation of a photovoltaic panel

The current–voltage (I–V) and power–voltage (P–V) characteristics of the photovoltaic panel obtained under standard test conditions ($T = 25^\circ\text{C}$ and $E = 1000 \text{ W/m}^2$) are depicted in the following figures.

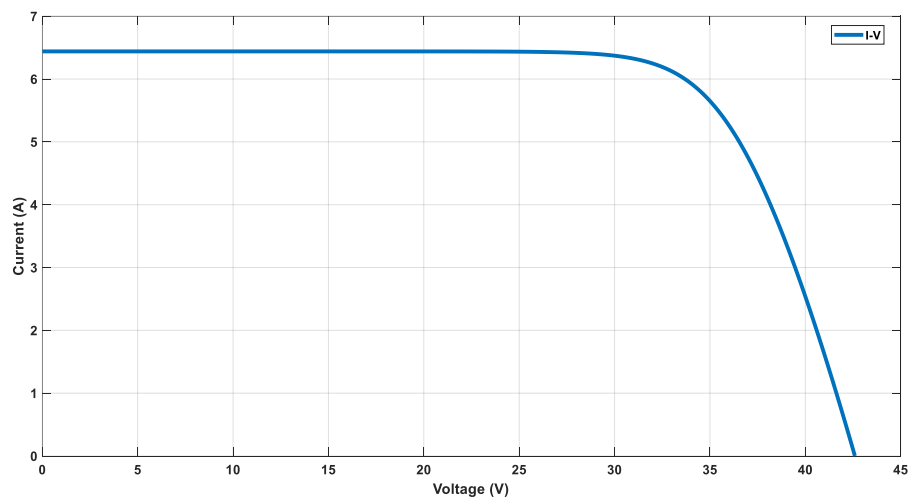


Figure II.3: Represents the I-V characteristic of a photovoltaic module

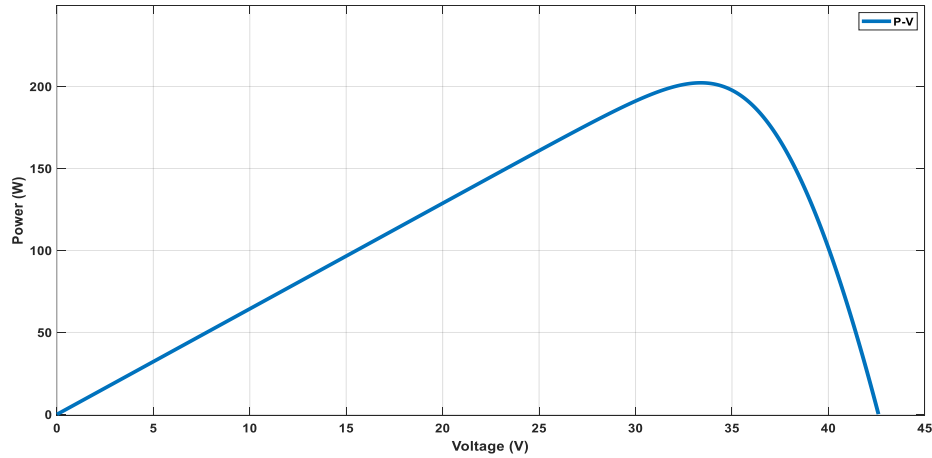


Figure. II.4: Represents the P-V characteristic of a photovoltaic module

II.4.1. Influence of illumination and temperature on the PV panel

Figures II.5 and II.6 illustrate the variation of current and power as functions of voltage under different irradiance levels while maintaining a constant temperature of 25°C. The power–voltage (P–V) characteristics exhibit distinct maximum points, corresponding to the Maximum Power Points (P_{max}) of the photovoltaic module. Furthermore, for a fixed temperature, variations in irradiance significantly affect the current–voltage (I–V) characteristics, with the short-circuit current (I_{sc}) increasing almost proportionally to the irradiance level. This behavior highlights the strong dependence of photovoltaic current generation on incident solar radiation.

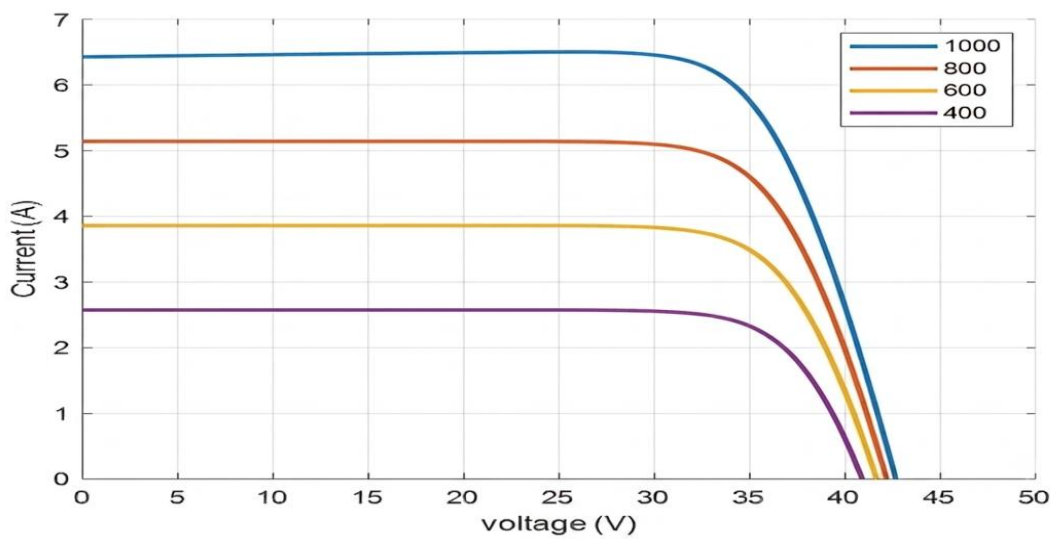


Figure. II.5: I–V characteristic curves of a (PV) panel under different irradiance conditions

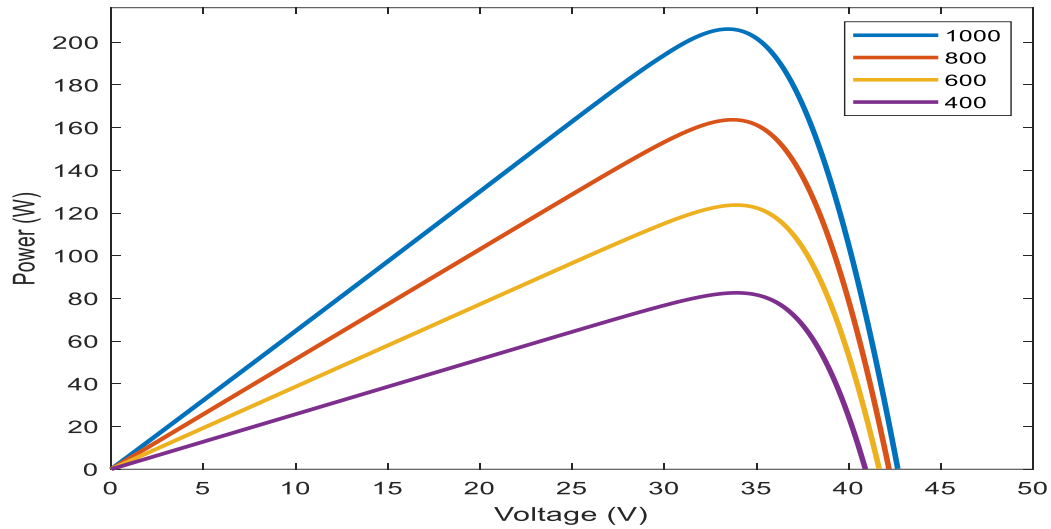


Figure. II.6 : P-V Curve of a (PV) Module at Various Irradiance Levels

II.4.2. Influence of temperature on the cell

Temperature is a key factor affecting the performance and behavior of solar cells. Variations in temperature significantly influence the electrical characteristics of a photovoltaic (PV) generator. Figure II.7 and II.8 illustrate the changes in the PV panel characteristics as a function of temperature under constant irradiance conditions. In these figures, the solar irradiance is maintained at 1000 W/m², allowing the effect of temperature on the PV module performance to be clearly observed.

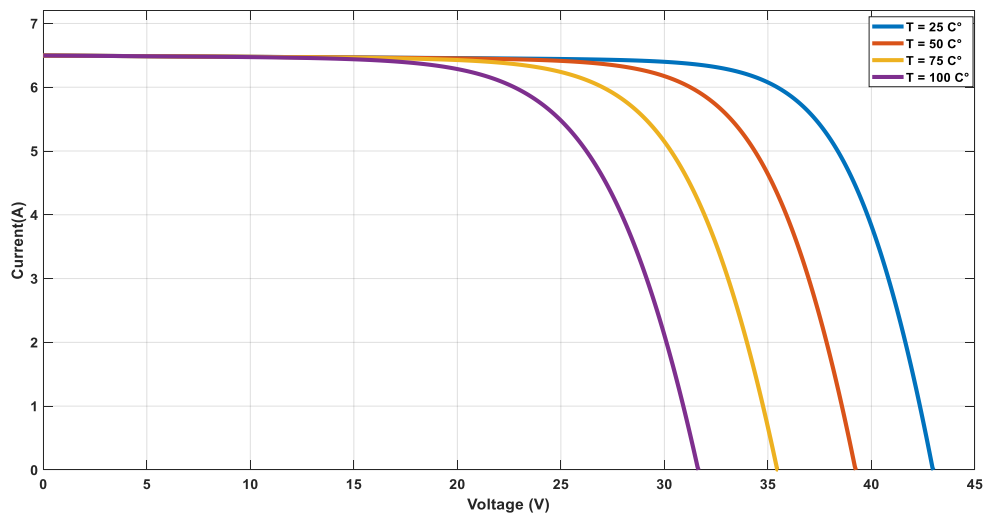


Figure. II.7: (I-V) characteristics curves for a solar panel at different temperatures

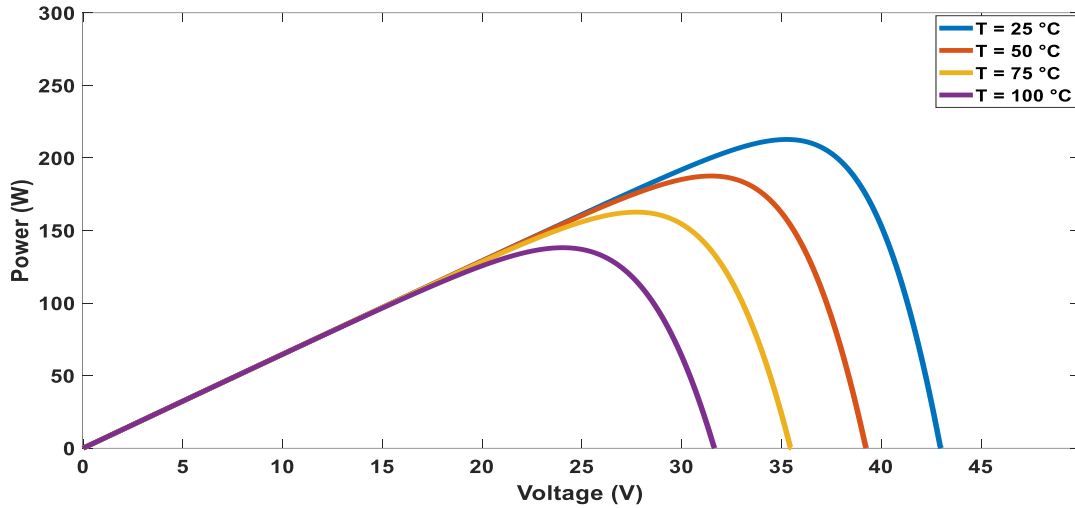


Figure. II.8: Influence of temperature on the P-V characteristic of a PV module

II.5. Model of the Boost Converter

The term boost converter originates from its ability to provide an average output voltage V_s greater than the input voltage V_{in} , as presented in Figure II.9 [36] .

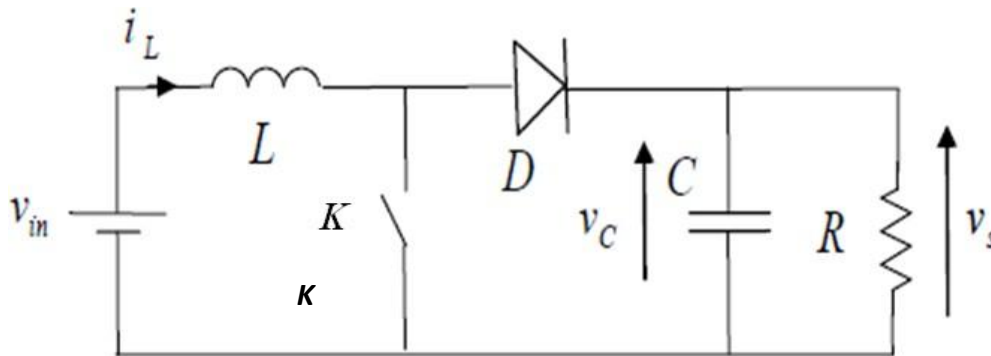


Figure. II.9: Boost Converter Diagram

This chopper consists of four essential components: an inductor L , a filtering capacitor C , a diode D , and a controllable switch S (such as a MOSFET or IGBT). The state of the switch is represented by a control signal $U \in \{0, 1\}$, defined as follows

$U = 1$: The switch is closed (conducting)._

$U = 0$: The switch is open (blocked).

For a given ' α ' duty cycle, and in the DC conduction regime, the average voltage and the current at the output are given by [38].

$$V_s = \frac{V_e}{1 - \alpha} \quad (\text{II. 15})$$

$$I_s = (1 - \alpha)I_e \quad (\text{II. 16})$$

The duty cycle α is between 0 and 1, so the output voltage V_s is necessarily greater than the input voltage V_e .

II.5. 1. Working principle

Since the circuit is powered by a V_i voltage source, the operation of a Boost converter can be divided into two distinct phases depending on the state of the K-switch [37].

II.5. 1.1. the passing state

When the switch is closed ($0 < t < DT$) (Figure 2.5), the current in the inductor increases and the energy is stored as magnetic energy. The Di diode is then blocked and the load is consequently disconnected from the power supply.

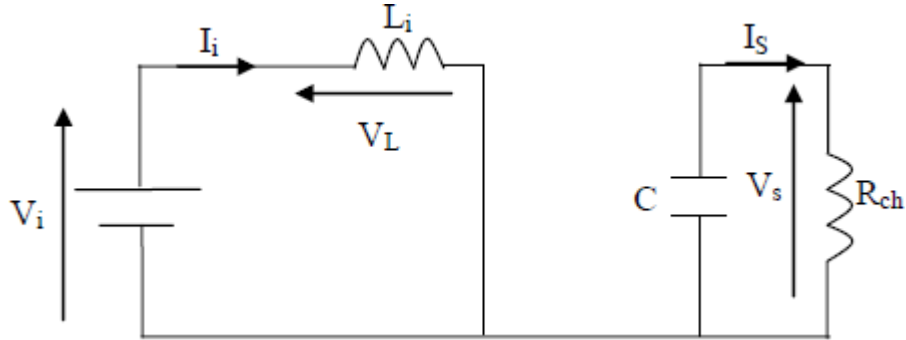


Figure. II.10: Boost diagram (S closed).

When the switch is closed (ON), the energy is stored in the coil, and the dynamics of the lift transducer are described by the following differential equations.

$$L \frac{di_L}{dt} = V_i \quad (\text{II. 17})$$

$$C \frac{dv_s}{dt} = -\frac{v_s}{R} \quad (\text{II. 18})$$

II.5.1.2.Blocked state

At time $t = DT$, the switch K opens Figure II.11, the emf of the inductance is added to that of the generator, as a result of the inductance being placed in series with the generator (voltage raising effect). The diode is then passed through, the current passes through the inductor, the capacitor and the charge. This results in a transfer of accumulated energy to capacity[38].

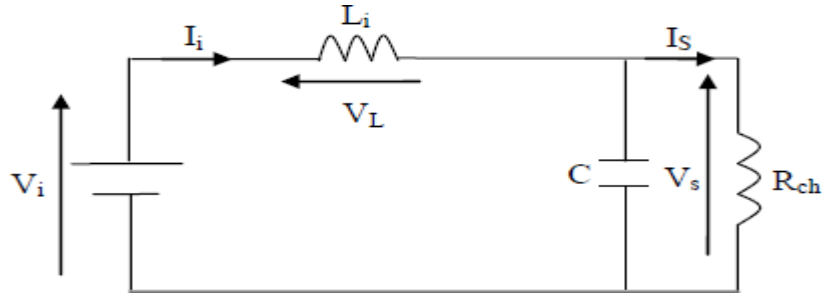


Figure. II.11: Boost diagram (open K)

When the switch is opened (OFF), the energy stored in the coil is transferred to the load and capacitor, and the state equations are given as follows.

$$L \frac{di_L}{dt} = V_i - v_s \quad (II. 19)$$

$$C \frac{dv_s}{dt} = i_L - \frac{v_s}{R} \quad (II. 20)$$

During the operation of the chopper, the transistor will be switched to a constant frequency f_s with a closing time $t_{on} = \alpha T_s$ and an opening time $t_{off} = (1-\alpha) T_s$, where:

$T_s = 1/f_s$: is the switching period

α : the duty cycle of the switch

II.6. Simulation of Boost converter in Matlab-Simulink

The simulation of a Boost Converter in MATLAB/Simulink is used to study its behavior and performance before practical implementation. The converter increases a low DC input voltage to a higher output voltage using electronic components such as a MOSFET, inductor, diode, and capacitor. The simulation allows the analysis of output voltage, current, and efficiency, helping to optimize the design under different operating conditions.

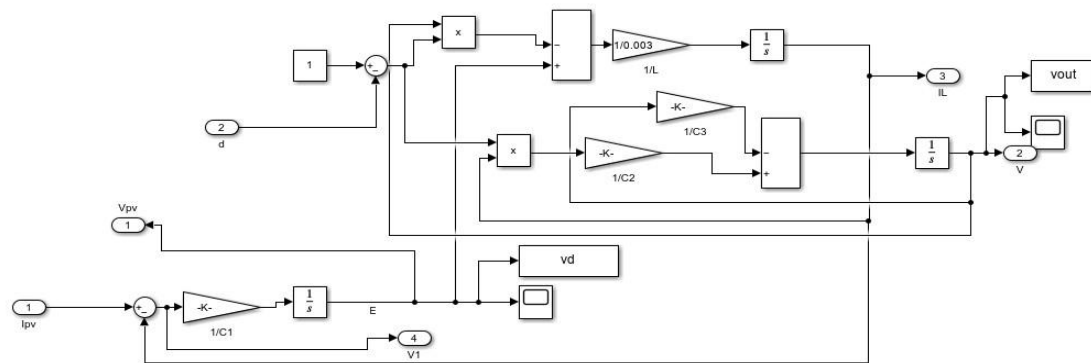


Figure. II.12: Boost chopper block diagram

II.6.1. Simulation result of boost converter

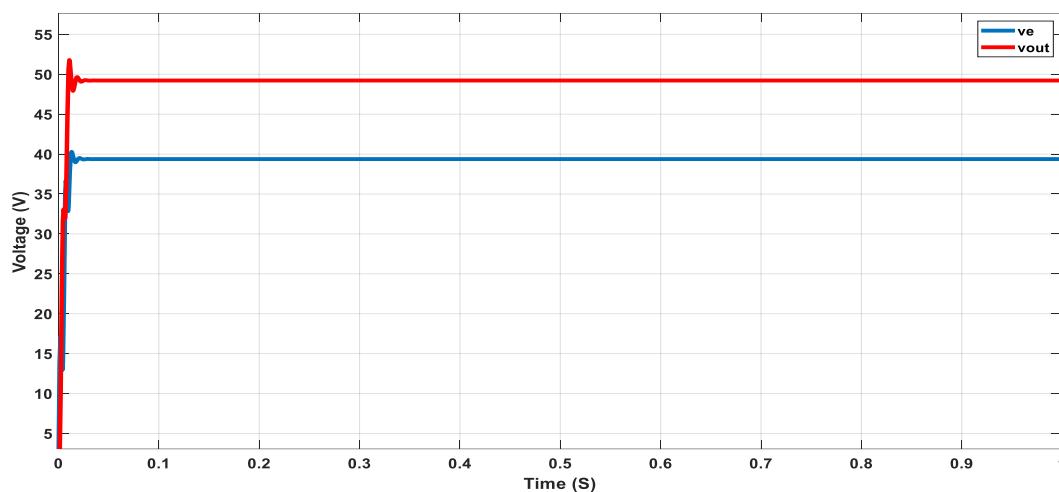


Figure. II.13: Result of Ve and Vout in duty 0.2

Add the simulation when alpha 0.2 ,0.5 and 0.8

II.7. MPPT Controle

An MPPT algorithm 'Maximum Power Point Tracking' is an algorithm for tracking the maximum power point of a nonlinear electrical generator. As a result, for the same illuminance, the power delivered will be different depending on the load. An MPPT controller therefore makes it possible to control the static converter connecting the load and the photovoltaic panel in such a way as to continuously supply the maximum power to the load at all times. The energy delivered by photovoltaic panel.

depends on a complex nonlinear equation relating solar radiation, temperature, and resistance [39].

II.7.1. Different MPPT techniques

In order to optimize the energy efficiency of solar panels, the Maximum Power Point Tracking (MPPT) technique is essential to extract the maximum power (P_{max}) under varying irradiation and temperature conditions. Several control methods exist, ranging from classic solutions to intelligent algorithms, distinguished by their complexity, accuracy and speed [40].

II.8. Perturbation & Observation (P&O) method

a- Definition

The P&O method is a widely used approach in the field of MPPT, due to its simplicity. It only requires measurements of the output voltage of the generator and its output current. The principle of this algorithm is to perform a perturbation on the voltage of the PV panel while acting on the duty cycle α . Indeed, following this disturbance, we calculate the power supplied by the PV panel at time k , then we compare it to the $(k-1)$. If the power increases, we approach the point of power maximum and the variation in the duty cycle is maintained in the same direction power decreases, we move away from the point of maximum power. So, we have to reverse the meaning of the variation of the duty cycle as illustrated in Figure II.14 [41].

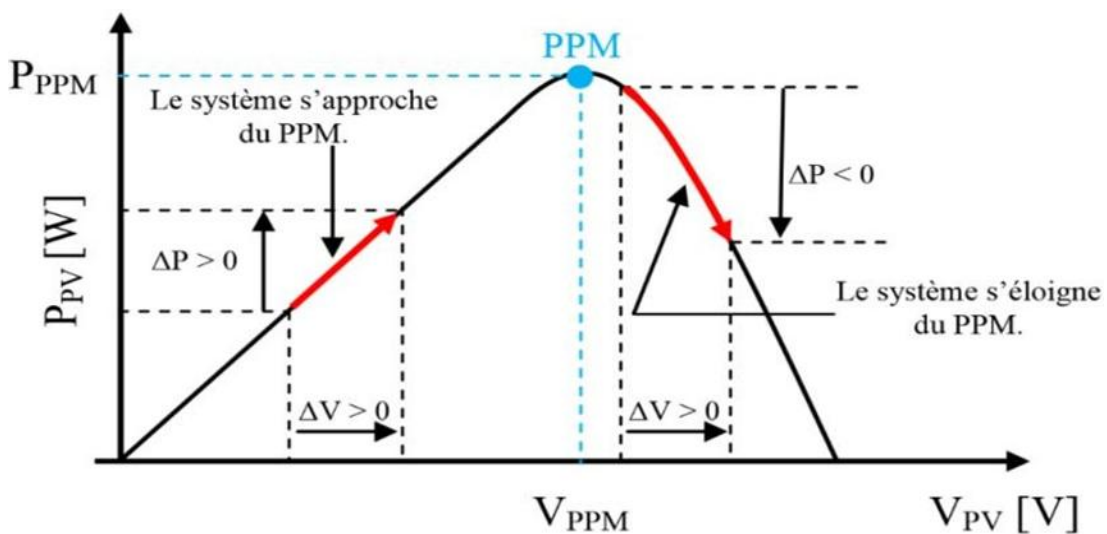


Figure. II.14: Operating characteristics of the P&O method.

b - How the P&O algorithm works

First case: $\Delta P_{pv} > 0$ and $\Delta V_{pv} > 0$

In this case the operating point is to the left of the MPP; in addition ΔV_{pv} is positive, so we are in the right direction. For the next iteration, we increase the voltage of the photovoltaic field. This can be achieved by decreasing the duty cycle. Let [41].

$$(k) = \alpha(k - 1) - \Delta\alpha \quad (II. 21)$$

Second case: $\Delta P_{pv} > 0$ and $\Delta V_{pv} < 0$

The operating point is to the right of the MPP; in addition ΔV_{pv} is negative, the search for the MPP is done in the right direction. We will therefore continue to decrease the voltage (thus increasing the duty cycle) for the next iteration. Let:

$$(k) = \alpha(k - 1) + \Delta\alpha \quad (II. 22)$$

Third case: $\Delta P_{pv} < 0$ and $\Delta V_{pv} < 0$

The operating point is to the left of the MPP; and as ΔV_{pv} is negative we go. In the next iteration, the direction of the search must be corrected by increasing tension. So be it[42],

$$(k) = \alpha(k - 1) - \Delta\alpha \quad (II. 23)$$

Fourth case: $\Delta P_{pv} < 0$ and $\Delta V_{pv} > 0$

The current operating point is to the right of the MPP; in addition ΔV_{pv} is positive, the search is therefore being done in the wrong direction. For the next iteration, we're going to decrease the voltage (thus increase the duty cycle). Let us therefore have:

$$(k) = \alpha(k - 1) + \Delta\alpha \quad (II. 24)$$

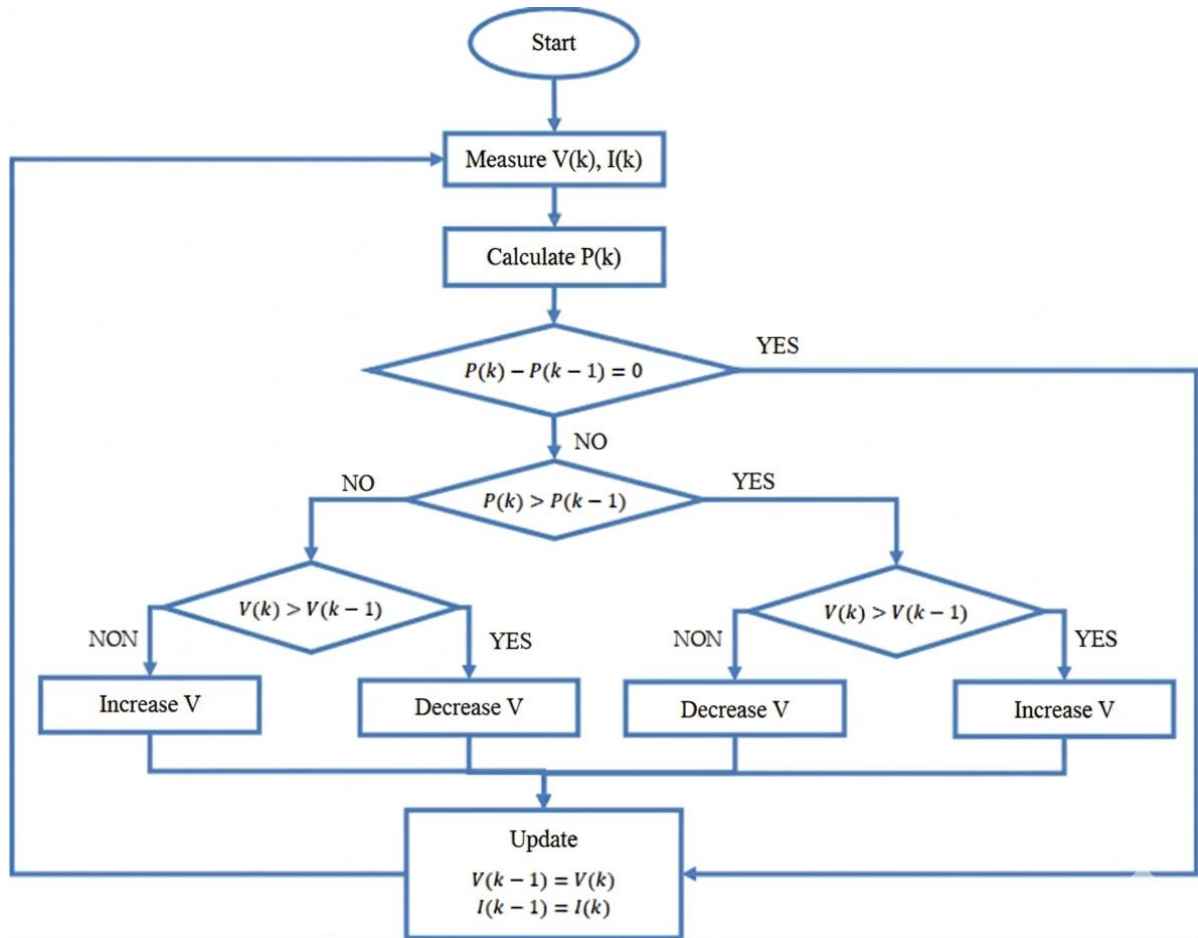


Figure. II.15: Flowchart of the MPPT algorithm of the perturbation & observation.

The P&O method is now widely used because of its ease of implementation, however it has some problems related to the oscillations around the PPM that it generates in a steady state because the PPM search procedure must be repeated periodically, forcing the system to oscillate constantly around the PPM, once the latter is reached. These oscillations can be minimized by reducing the value of the perturbation variable. However, a low increment value slows down the PPM search, so a trade-off must be found between accuracy and speed. This makes this order difficult to optimize[43].

II.8.1.Simulation Results

The P&O, FLC, and PSO MPPT techniques were simulated simultaneously under the same irradiance variations (1000–700–980 W/m²) and identical operating conditions to ensure a fair comparison of their performance.

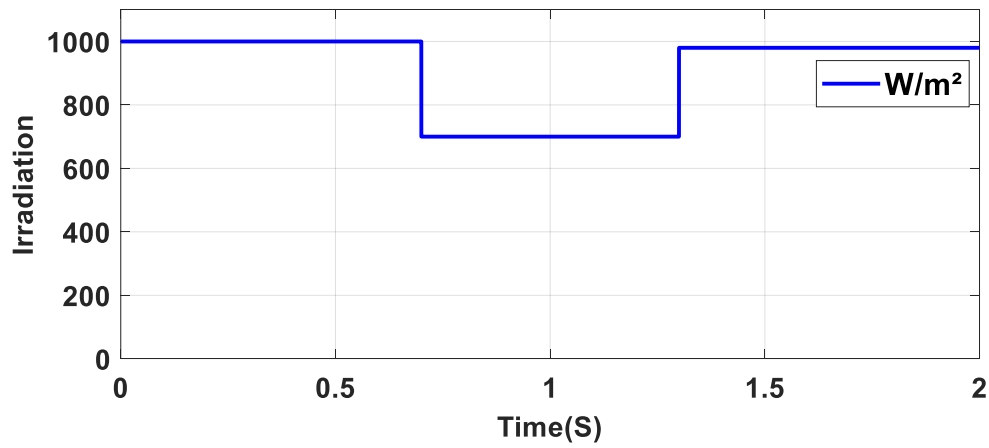


Figure. II.16: illuminance curve

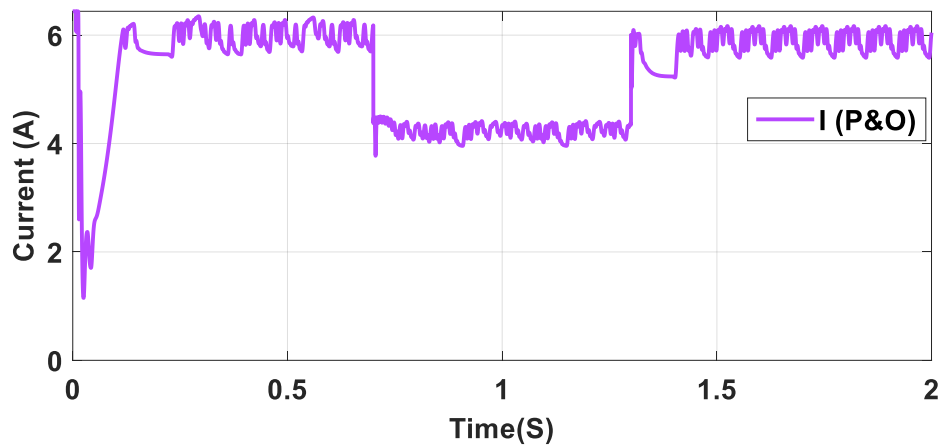


Figure. II.17: Current Response of the P&O MPPT Algorithm

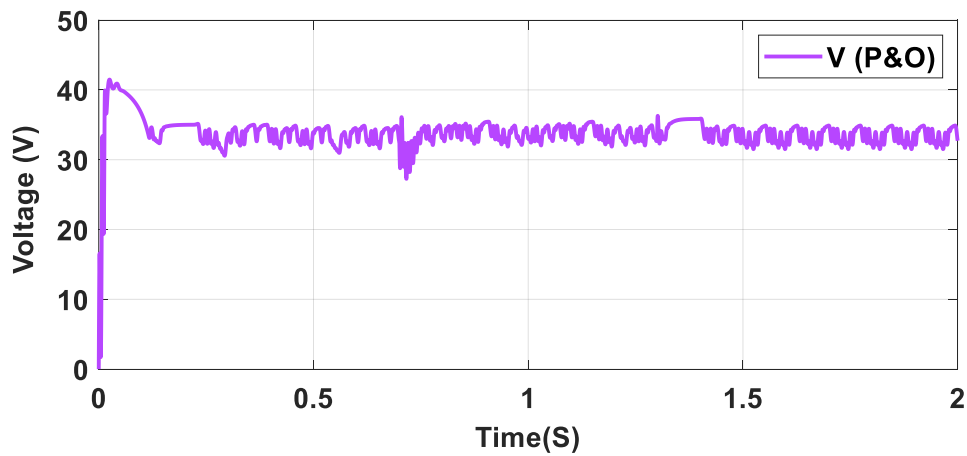


Figure. II.18 : Voltage Response of the P&O MPPT Algorithm

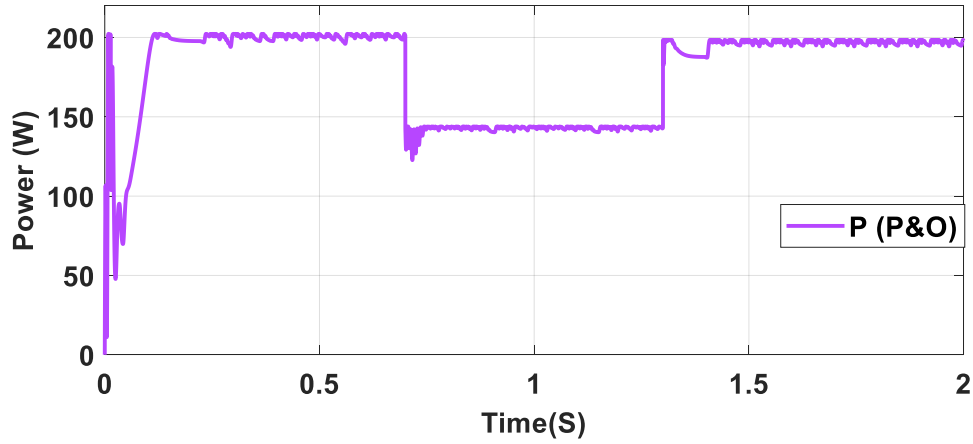


Figure. II.19: Power Response of the P&O MPPT Algorithm.

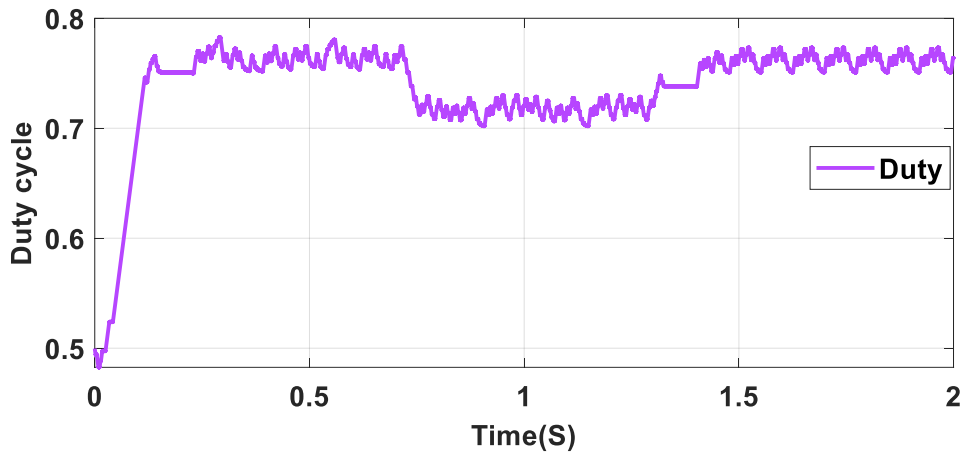


Figure. II.20: Graph of the Duty cycle.

-Discution

The simulation results demonstrate the good dynamic performance of the P&O algorithm under abrupt variations in solar irradiance. The current responds rapidly and proportionally to changes in the irradiation level as shown in (fig.II.17), while the voltage remains nearly constant with only minor transient deviations (fig.II.18). This behavior enables efficient and fast tracking of the Maximum Power Point (MPP) as illustrated in (fig.II.19), ensuring optimal energy extraction from the photovoltaic system. In addition, the Duty Cycle is automatically adjusted to maintain proper system operation and effective matching between the PV generator and the load as shown in (fig.II. 20). Although slight oscillations around the operating point are observed, they represent an inherent characteristic of the algorithm. Overall, the results confirm the effectiveness.

II.9. MPPT control by the fuzzy logic method

Fuzzy Logic Control (FLC) is one of the most efficient methods for extracting the maximum power from a photovoltaic panel, especially in the face of sudden variations in radiation [44] .

illustrates the basic structure of the fuzzy MPPT controller. Generally, it consists of three main components: fuzzification, inference, and defuzzification.

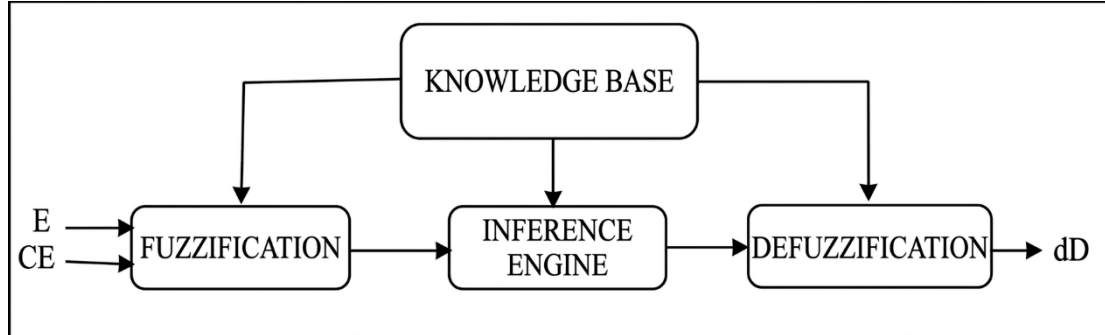


Figure. II.21: block diagram of the fuzzy logic-based algorithm

The error E and the error change CE and the output variable is the variation of the duty cycle dD . Fuzzification allows the conversion of input physical variables into fuzzy sets [45] .

II.9. 1. Principle of Fuzzy Logic

The general principle and basic theory of fuzzy logic is the description of a phenomenon that generally contains fuzzy expressions such as: Hot, cold. Fast, slow. Large, medium, small. Max, min. Positive, zero, negative... etc. The constituent elements of the basic theory of fuzzy logic are: Linguistic variables, fuzzy sets, and membership functions [46].

II.9.1.1. Fuzzification

The purpose of fuzzification is to define the membership functions for the different variables that allows the input variables to be blurred. A preliminary step is to define a maximum allowable variation interval for input variables. The goal of fuzzification is to transform input variables into linguistic variables or fuzzy variables. In our case,

we have two input variables which are the error $E(k)$ and the error variation CE at sampling time k which are defined as follows[47].

$$E = \frac{P(K) - P(K - 1)}{V(K) - V(K - 1)} \quad (II.25)$$

$$CE = E(K) - E(K - 1) \quad (II.26)$$

illustrates the membership functions adopted for the input and output variables of the fuzzy logic controller.

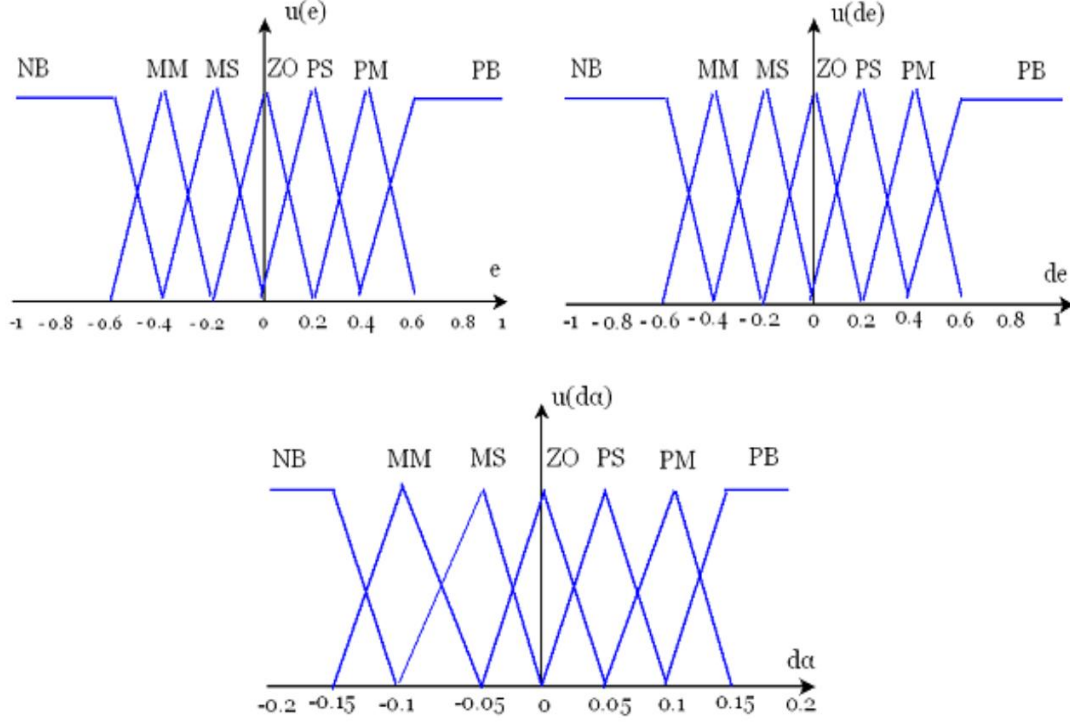


Figure. II.22: Basic structure of fuzzy control

II.9.1.2. Inference Method

The rule matrix used in this study is presented in Table 3.2. The error variable (e) is transformed into linguistic variables using five fuzzy subsets previously defined. In this work, the Mamdani method was selected as the fuzzy inference approach. This method employs the “MIN” operator for the logical “AND” operation and the “MAX” operator for the logical “OR” operation [46].

Table. 2.2: Rules of Inference.

de \ e	MB	MM	MS	ZO	PS	PM	PB
MB	MB	MB	MB	MB	MM	MS	ZO
MM	MB	MB	MB	NM	MS	ZO	PS
MS	MB	MB	MM	MS	ZO	PS	PM
ZO	MB	MM	MS	ZO	PS	PM	PB
PS	MM	MS	ZO	PS	PM	PB	PB
PM	MS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

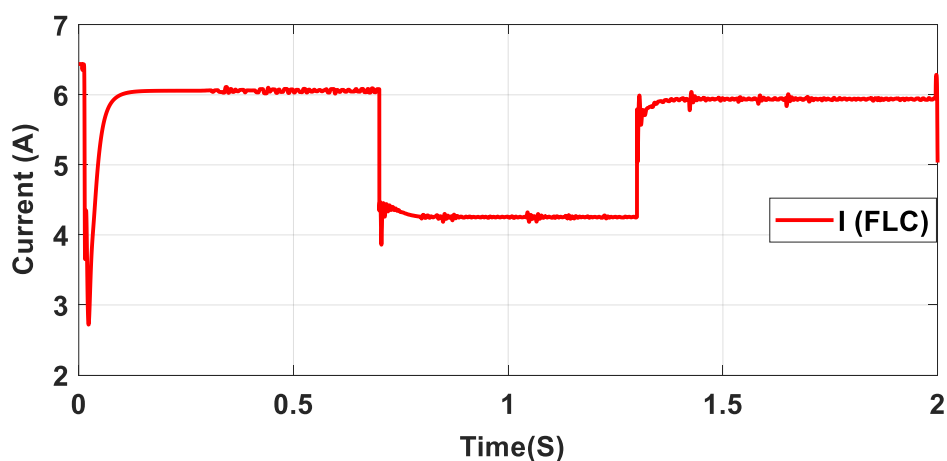
II.9.1.3. Defuzzification

Finally, we must perform the opposite operation of fuzzification, here we must calculate a numerical value understandable by the external environment from a fuzzy definition and this is the purpose of defuzzification[47].

The center of gravity of the membership function is computed to determine the crisp output values. It is expressed as follows:

$$\Delta D = \frac{\sum_{i=1}^n \mu(D_i) \cdot D_i}{\sum_{i=1}^n \mu(D_i)} \quad (\text{II. 27})$$

II.9.2. Results Simulation

**Figure. II.23:** Current Response of the FLC MPPT Algorithm .

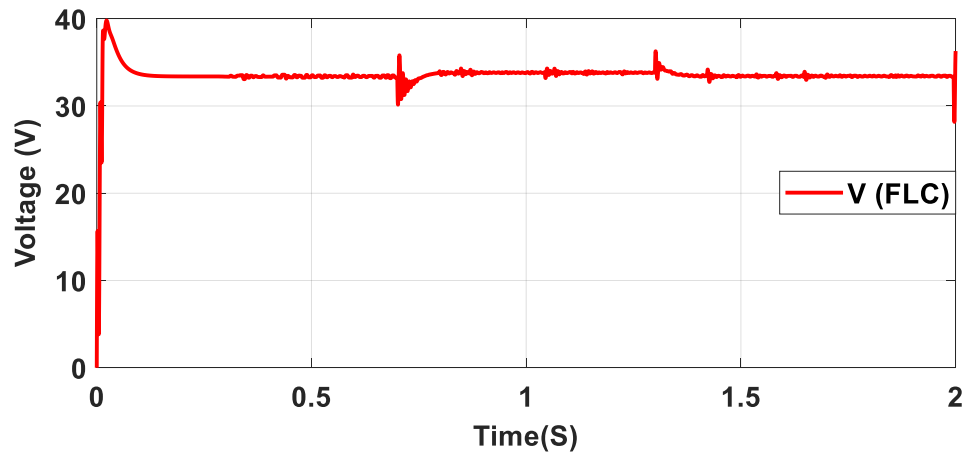


Figure. II.24: Voltage Response of the FLC MPPT Algorithm.

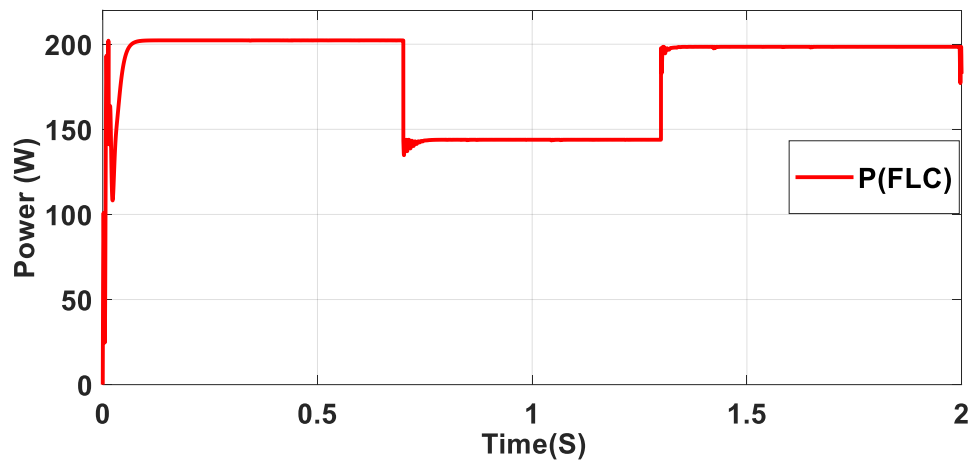


Figure. II.25 : Power Response of the FLC MPPT Algorithm.

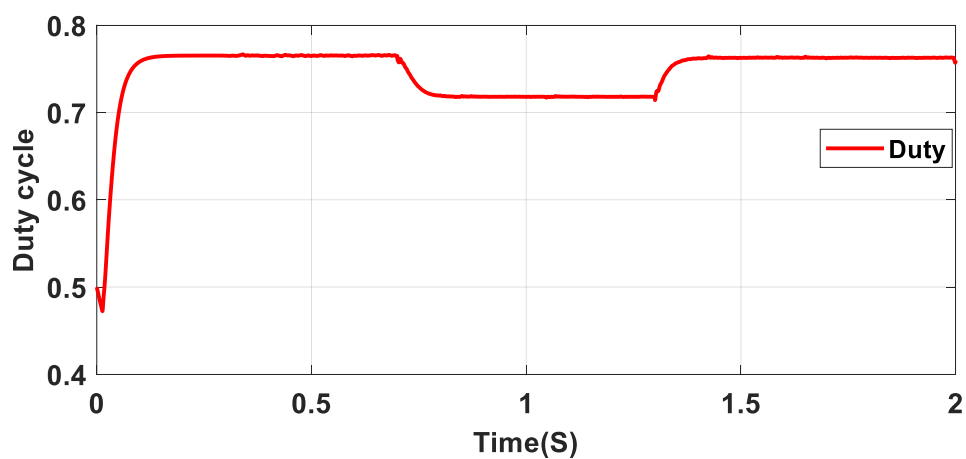


Figure. II.26: Graph of the Duty cycle.

- Discussion

The simulation results show that the Fog Logic Algorithm (FLC) has a high response speed and great accuracy in tracking the maximum power point (MPP) when solar radiation changes as illustrated in (fig.II.25). The current responded directly to radiation changes as shown in (fig.II.23), while the voltage maintained a near-constant stability around its optimal value deviations (fig.II.24). The Duty Cycle has also been automatically adjusted to ensure optimal system operation as shown in (fig.II. 26). The results highlighted the algorithm's ability to significantly reduce oscillations and achieve high stability, enhancing the efficiency of energy extraction from the photovoltaic system under various operating conditions.

II.10. Particle Swarm Optimization (PSO) method

The Particle Swarm Optimization (PSO) algorithm is considered one of the most widely used artificial intelligence and evolutionary algorithms in the field of renewable energy, due to its simple structure, ease of implementation, and fast computational speed. This technique is distinguished by its high capability to accurately track the Maximum Power Point (MPPT) of photovoltaic systems despite variations in environmental conditions such as solar irradiance and temperature [48] .

The operating principle of the PSO algorithm is based on an iterative process inspired by the collective behavior of birds and schools of fish while searching for food. Each particle represents a potential solution in the search space, where its position corresponds to the output voltage of the photovoltaic generator, while the objective function is defined by the output power of the PV system. During the iterations, each particle updates its position and velocity according to its own best experience (P-best) and the global best experience of the swarm (G-best). Consequently, the algorithm effectively combines local search and global search in order to converge rapidly toward the maximum power point with high stability and accuracy.

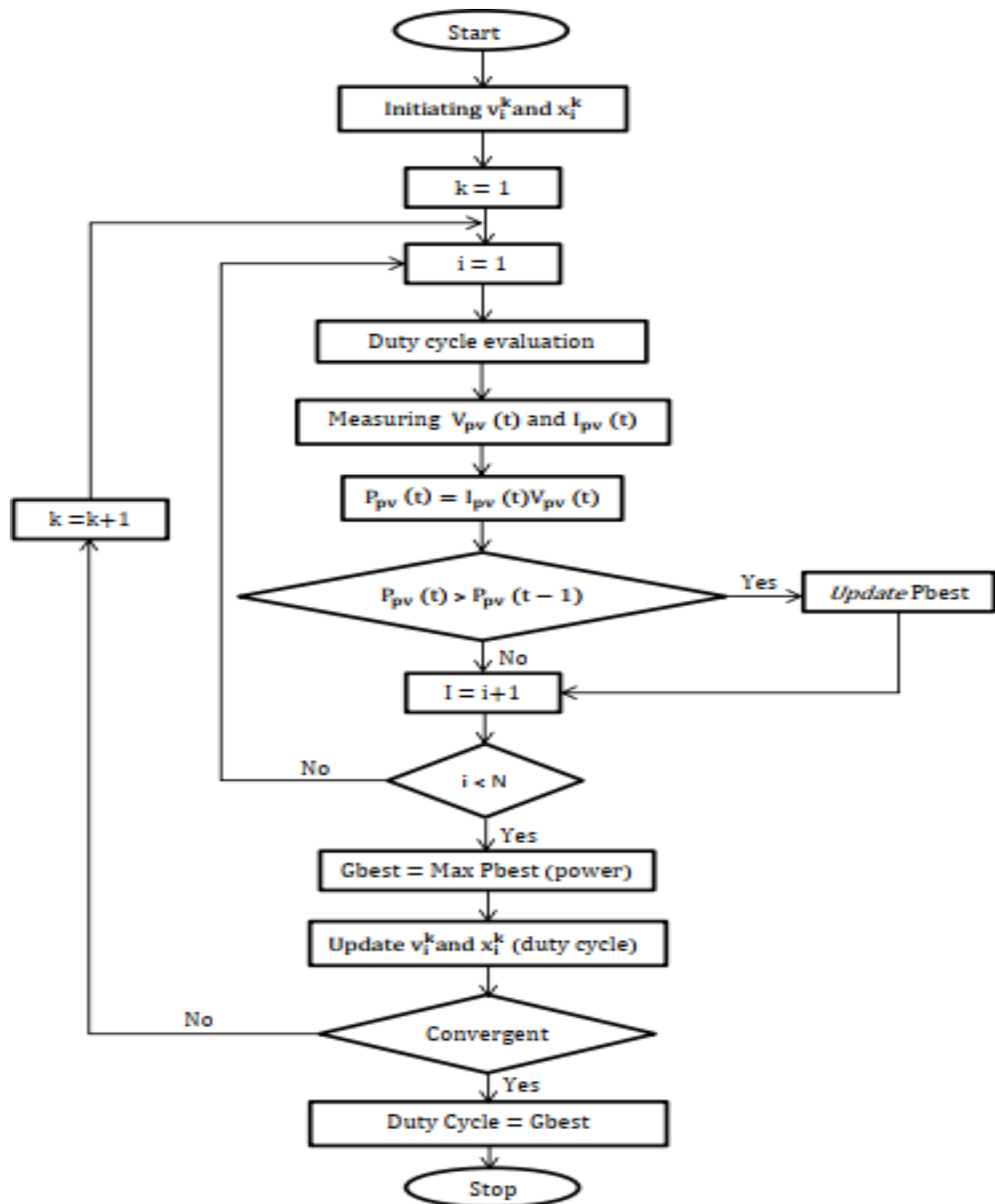


Figure. II.27: PSO Algorithm.

II.10.1. Simulation Results

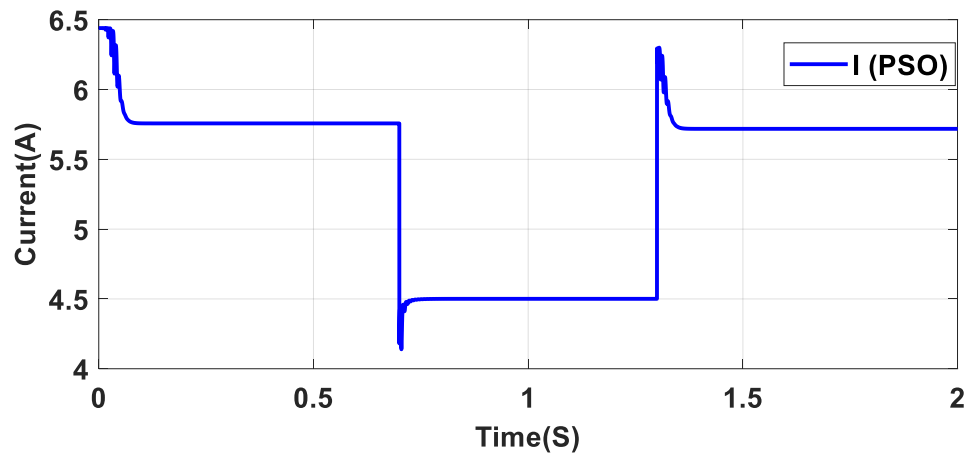


Figure. II.28: Current Response of the PSO MPPT Algorithm.

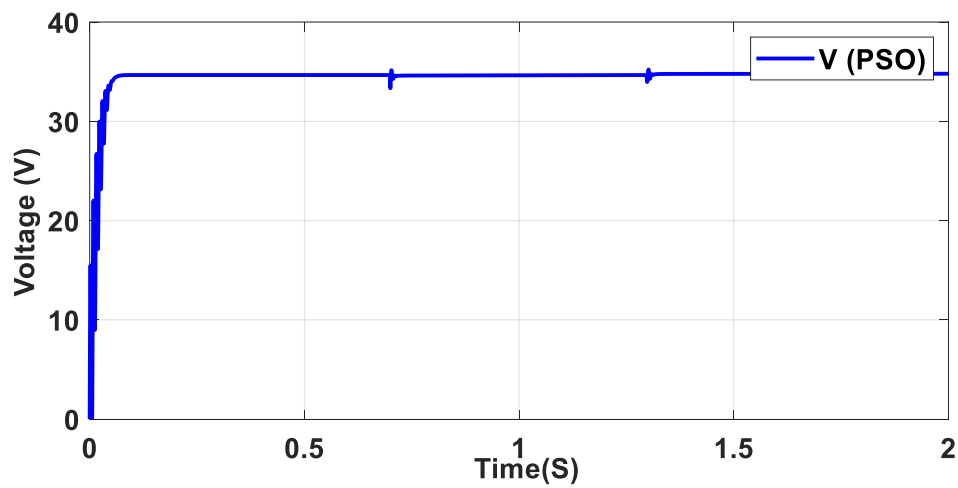


Figure. II.29: Voltage Response of the PSO MPPT Algorithm.

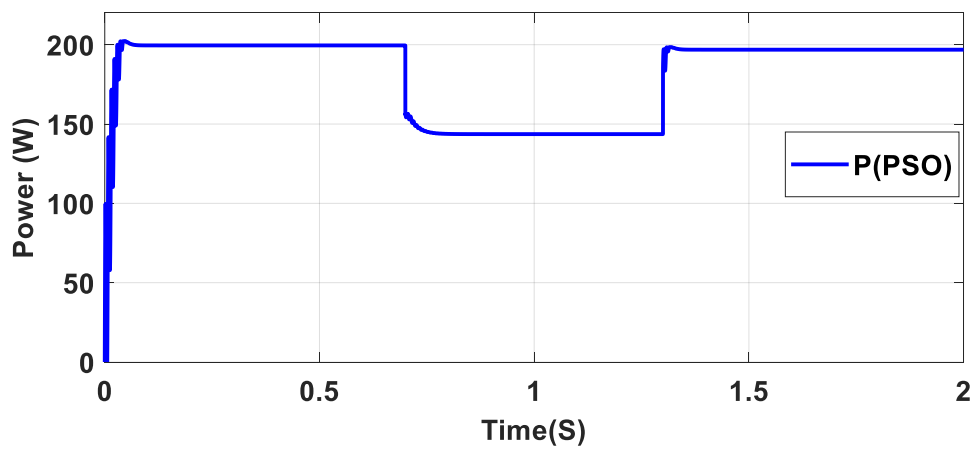


Figure. II.30: Power Response of the PSO MPPT Algorithm.

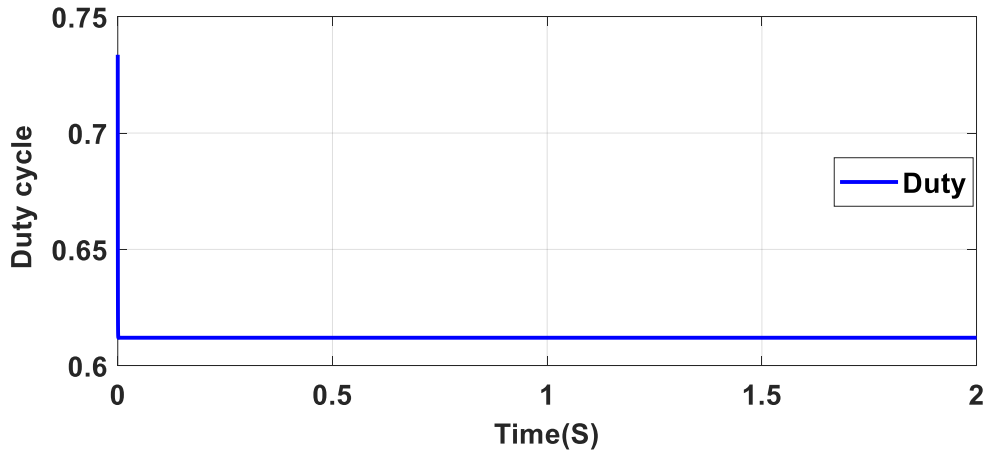


Figure. II.31: Graph of the Duty cycle

- Discussion

The simulation results show that the Fog Logic Algorithm (FLC) has a high response speed and great accuracy in tracking the maximum power point (MPP) when solar radiation changes as illustrated in (fig.II.30). The current responded directly to radiation changes as shown in (fig.II.28), while the voltage maintained a near-constant stability around its optimal value deviations (fig.II.29). The Duty Cycle has also been automatically adjusted to ensure optimal system operation as shown in (fig.II.31). The results highlighted the algorithm's ability to significantly reduce oscillations and achieve high stability, enhancing the efficiency of energy extraction from the photovoltaic system under various operating conditions.

II.11 .Comparative MPPT Methods of P&O, PSO, and FLC

Based on the numerical simulations performed in the MATLAB/Simulink environment, a precise comparison was carried out between three MPPT control techniques: the conventional P&O method, the Fuzzy Logic Controller (FLC), and the Particle Swarm Optimization (PSO) algorithm. The performance of these methods was evaluated under sudden variations in weather conditions applied to a DC–DC boost converter. Particular attention was given to the output power delivered by the photovoltaic system, as the extracted maximum power constitutes the main criterion for assessing the effectiveness of each MPPT technique.

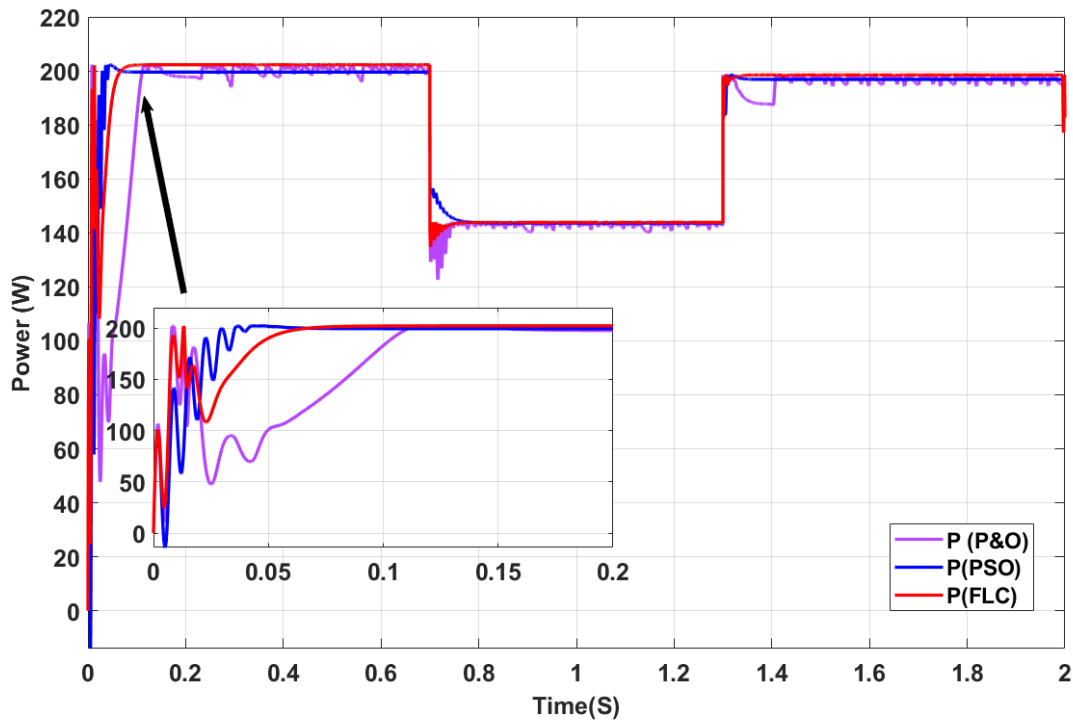


Figure. II.32: Comparison of MPPT algorithms (P&O, PSO, and FLC) under dynamic responses.

The Particle Swarm Optimization (PSO) algorithm demonstrates the best performance in terms of stability and efficiency, as it effectively adapts to sudden changes in irradiance and temperature while minimizing oscillations. It can also accurately track the maximum power point under partial shading conditions, making it more reliable in practical applications.

The Fuzzy Logic Controller (FLC) performs well under steady-state conditions, but its reliance on predefined rules leads to transient fluctuations during rapid environmental changes, which reduces overall stability compared to PSO.

The Perturb and Observe (P&O) method is the simplest approach; however, it is the least efficient due to continuous oscillations around the maximum power point and poor performance under fast-changing or partially shaded conditions.

Thus, the PSO algorithm is considered the best practical choice due to its high stability, its flexibility in the face of turbulence, and its ability to achieve the highest energy efficiency compared to both FLC and P&O.

II.12. Conclusion

This chapter presented the modeling and simulation of a photovoltaic system using three MPPT techniques: P&O, PSO, and FLC. The simulation results showed that the PSO and FLC methods track the maximum power point faster and with fewer oscillations compared to the conventional P&O algorithm, especially under changing irradiation conditions. Although the P&O method is simpler, it presents higher oscillations and lower efficiency. Overall, the PSO and FLC techniques provide better performance, while PSO remains more complex to implement.

CHAPTRE III

Implementation of the MPPT Controller

III.1. Introduction

In this chapter, the Maximum Power Point Tracking (MPPT) techniques, namely Perturb and Observe (P&O), Particle Swarm Optimization (PSO), and Fuzzy Logic Control (FLC), are implemented using the Texas Instruments LAUNCHXL-F28379D development board. The objective is to evaluate the real-time performance of these algorithms in extracting the maximum available power from a photovoltaic (PV) system under varying operating conditions.

III.2. System Components

III.2.1. PV panel

For the experimental implementation, a 200 W photovoltaic (PV) module was employed as the energy source. The selected module is based on monocrystalline silicon (Mono-Si) technology and consists of 72 series-connected photovoltaic cells. Owing to its high efficiency and reliability, this PV module is well suited for evaluating the performance of the implemented MPPT algorithms. The main electrical characteristics of the Condor CEM200M-72 photovoltaic module are :

Table III.1: Electrical and Mechanical Characteristics of the Condor CEM200M-72 Solar Panel

Maximum Power (P _{max})	200 W
Power Tolerance	±5%
Current at P _{max} (I _{mp})	5.48 A
Voltage at P _{max} (V _{mp})	38 V
Short Circuit Current (I _{sc})	5.75 A
Open-Circuit Voltage (VOC)	45 V
Nominal Cell Operating Temp (NOCT)	45 ± 2°C
Weight	14.5 Kg
Dimension	1580 × 808 × 45 mm
Maximum System Voltage	1000 V DC
Maximum Fuse Load	10 A
Cell Technology	Mono-Si

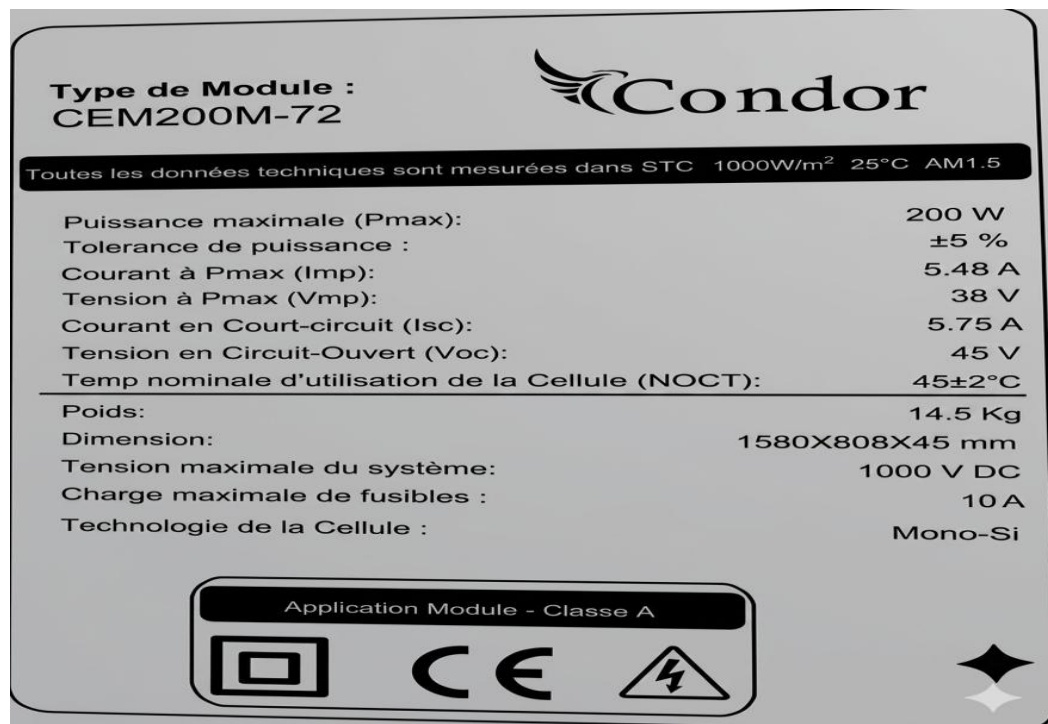


Figure. III.1: PV Panel Nameplate 200W

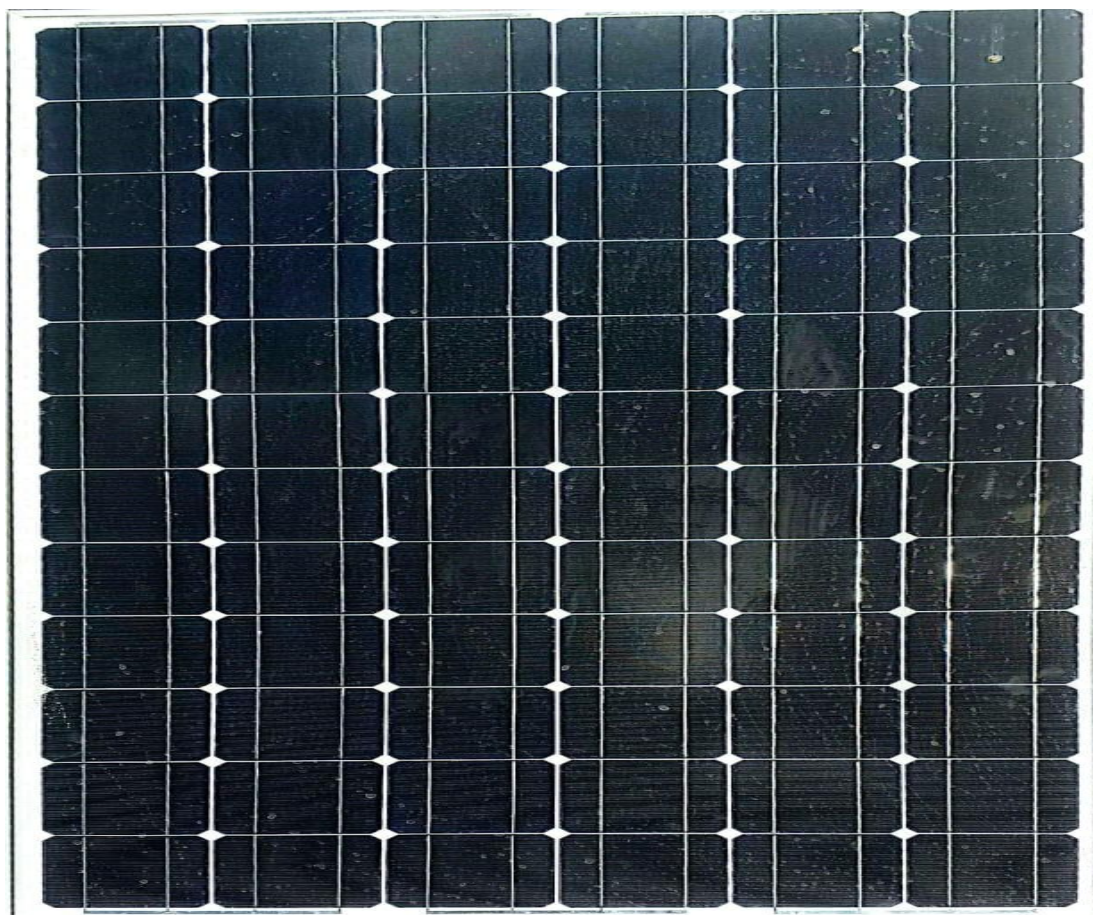


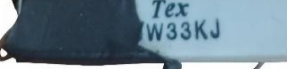
Figure. III.2: PV panel 200W

III.2.2.Design and Implementation of the Sensor Board

The sensor board was developed to measure and condition the voltage and current signals of the photovoltaic system before they are transmitted to the control unit. It incorporates sensing elements, operational amplifiers, resistors, capacitors, and filtering circuits to ensure accurate signal acquisition and noise reduction. The conditioned signals are scaled to levels compatible with the analog-to-digital converter (ADC) of the Texas Instruments LAUNCHXL-F28379D board. This board plays a key role in providing reliable real-time measurements, which are essential for the effective implementation and evaluation of the MPPT control algorithms.

III.3. The Components

Table .III.2 : Components of the Board

	Resistance 22 k ohm 4pcs
	Resistance 47 k ohm 2pcs
	Resistance 1 M ohm 2pcs
	Capacite 1 micro Farad 8pcs
	Capacite 2 nano Farad 2pcs
	Capacite 1 nano Farad 2pcs
	Resistance 100 ohm 2pcs
	Resistance 33k ohm 1W 1pcs
	Charge variable
	TL081 amplifier
	LV-28-P voltage sensor
	LA-25-NP Current Sensor

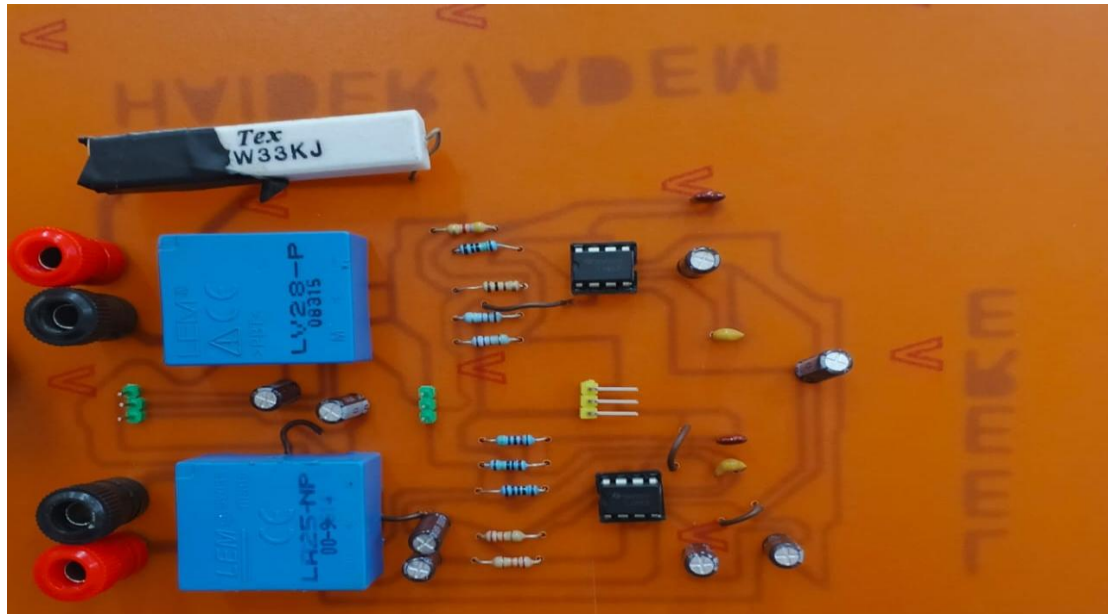


Figure. III.3: sensors circuit

III.3.1. Voltage sensor

To measure the PV voltage , we used the LEM LV 28-P Hall effect voltage sensor



Figure. III.4: LV-28-P voltage sensor

This voltage sensor requires a power supply of ± 12 V or ± 15 V to ensure proper operation. An input resistor R_1 is connected at the sensor input, and its value depends on the voltage to be measured in order to keep the current flowing through the primary windings below 10 mA. Another resistor R_m is connected at the sensor output, whose role is to calibrate and adjust the output voltage to the desired value[49].

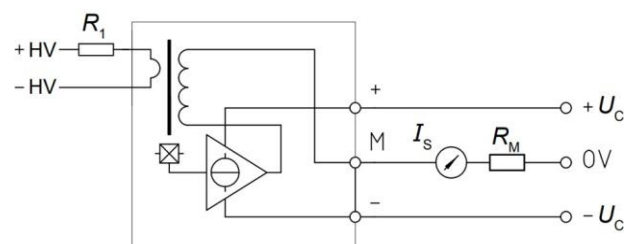


Figure .III.5: Circuit Diagram LV-28-P Voltage Sensor

III.3.2. Current sensor

The current measurement is performed using the LEM LA 25-NP sensor, which is based on the Hall Effect principle and provides galvanic isolation between the primary and secondary circuits. The sensor generates an output signal proportional to the current flowing through the primary conductor, enabling accurate and safe current measurement. Similar to the voltage sensor, the measured quantity is converted into a proportional output voltage that can be processed by the control system. However, unlike the voltage sensor, the LA 25-NP does not require an input resistor, since the current to be measured passes directly through the primary conductor of the sensor [50].



Figure .III.6: LA-25-NP Current Sensor

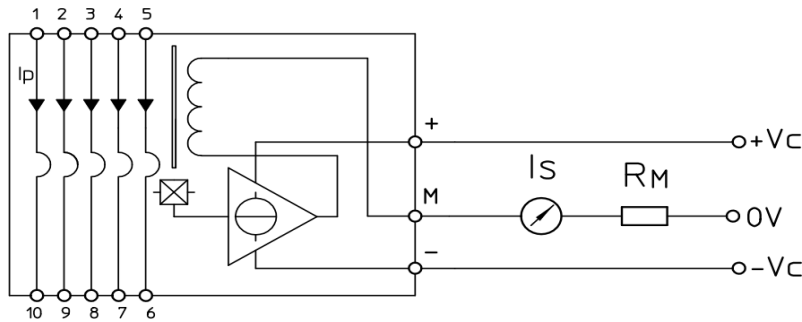


Figure. III.7: LA-25-NP Current Sensor Circuit Diagram

III.3.3. The TL081 amplifier

The TL081 is a high-performance operational amplifier widely used in signal conditioning and analog processing applications. Its pin configuration is illustrated in Figure III -7, where each pin is identified by a specific number and function. Pins 1 and 5 are dedicated to offset voltage adjustment, allowing compensation for internal offset errors and improving measurement accuracy. The TL081 is characterized by its high input impedance, wide bandwidth, and low power consumption, making it suitable for precision electronic circuits.

The detailed pinout of the TL081 operational amplifier is presented in Figure III-8.[51]

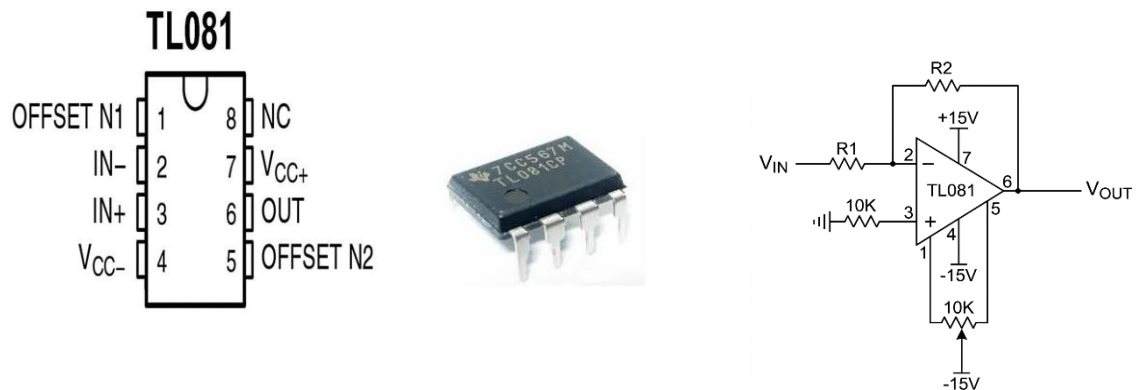


Figure. III.8: TL 081 Operational Amplifier

III.3.4. The DC-DC BOOST Converter

A practical model of the Boost Converter used in the proposed system. The circuit consists of an inductor to store energy, two capacitors to reduce ripple and improve voltage stability, a diode to direct the current and prevent its backflow, and a MOSFET power transistor that acts as an electronic switch. This transformer raises the continuous input voltage to a higher level at the output while maintaining proper operating efficiency and system stability.

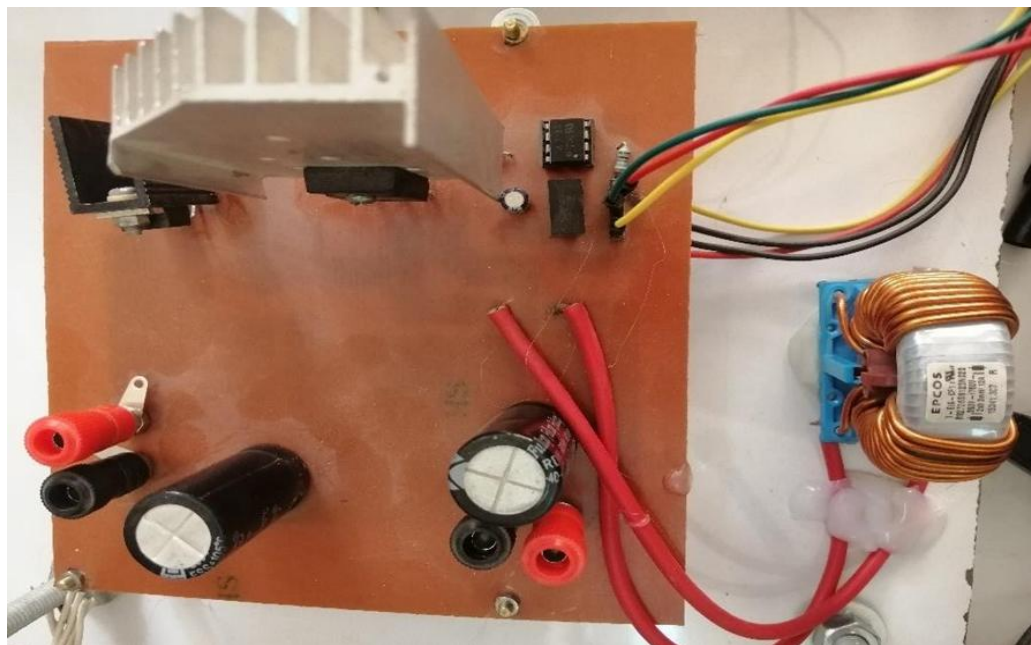


Figure .III.9: Diagram of the boost chopper(converter boost)

Table. III.3: Components and roulds of the Boost Converter Circuit

Component	Role
DC Voltage Source (Input)	Supplies the input DC voltage (E).
Thyristor	Opens and closes periodically to chop the voltage.
Diode	Ensures current continuity when the switch is open.
Inductor	Smoothes the output current to reduce ripples.
Capacitor	Smoothes the output voltage.
Load (Output)	Receives the controlled DC voltage

III.3.5.Transistor IRFP250N

This transistor is a high-efficiency electronic essential element that is used as a fast electronic switch or as a signal amplifier, allowing the passage of large electric currents to be controlled using a very small control voltage. It features a strong TO-247 casing that is intended to withstand high temperatures and can be mounted on a heat sink, and consists of three main terminals: the gate for control, the drain for the passage of current, and the source for the exit of the current and its connection to the ground[52]

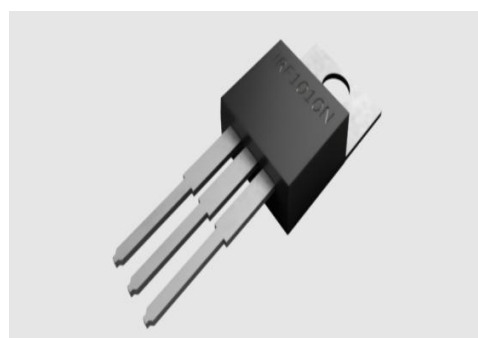
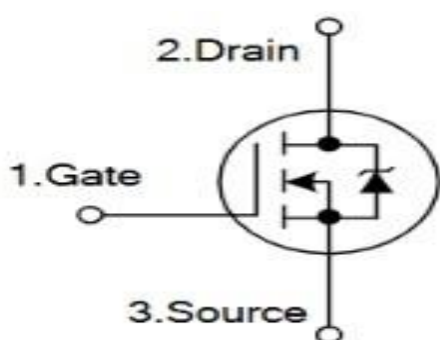


Figure .III.10 :Pin Configuration and Internal Structure of MOSFET Transistor

III.3.6.Dual Schottky Diode

A Dual Diode is an electronic element that integrates two diodes into a single, three-end package (such as TO-220) with the goal of reducing volume, simplifying connections, and improving cooling via a common heat sink. In the common cathode type, the middle leg is the common cathode, while the two side legs represent the anode

for each diode, and this type is widely used in calendor and power circuits such as DC-DC converters and inverters.

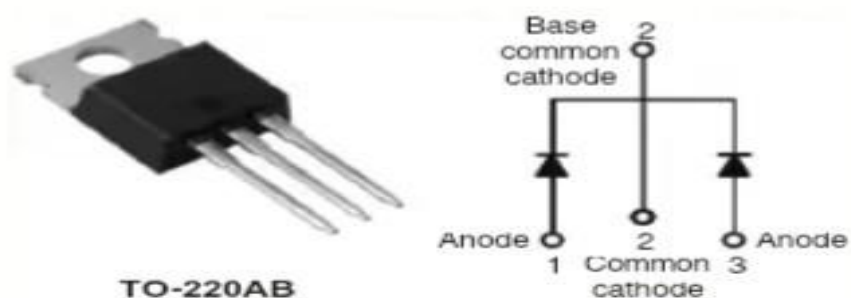


Figure .III.11: TO-220AB Dual Schottky Diode Pinout and Internal Schematic

III.3.7.TMS320F28379D LaunchPad™ Development Kit

The Texas Instruments LaunchXL-F28379D board is a development platform based on the C2000 family TMS320F28379D microcontroller. It has multiple digital input/output pins, high-precision analog inputs, as well as PWM outputs suitable for real-time control and power electronics applications. The board features a high-performance dual-core processor running at up to 200 MHz, an integrated USB interface, BoosterPack-compatible expansion connectors, an onboard debugger, and a reset button. It contains all the necessary elements for the development and programming of embedded systems. Simply connect it to a computer via a USB cable or power it from an external source to start control and simulation applications.[53]

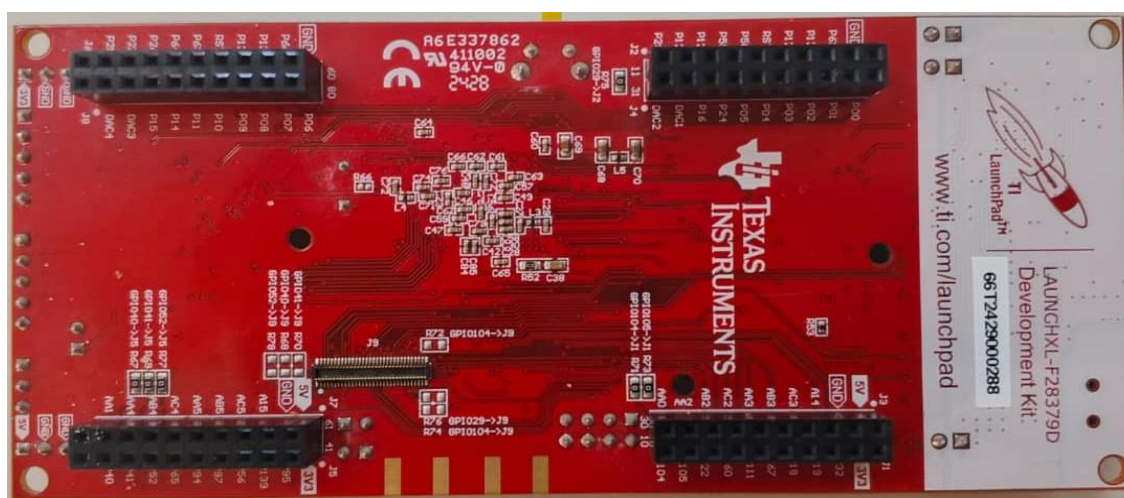


Figure .III.12: Making up the card TMS320F28379D

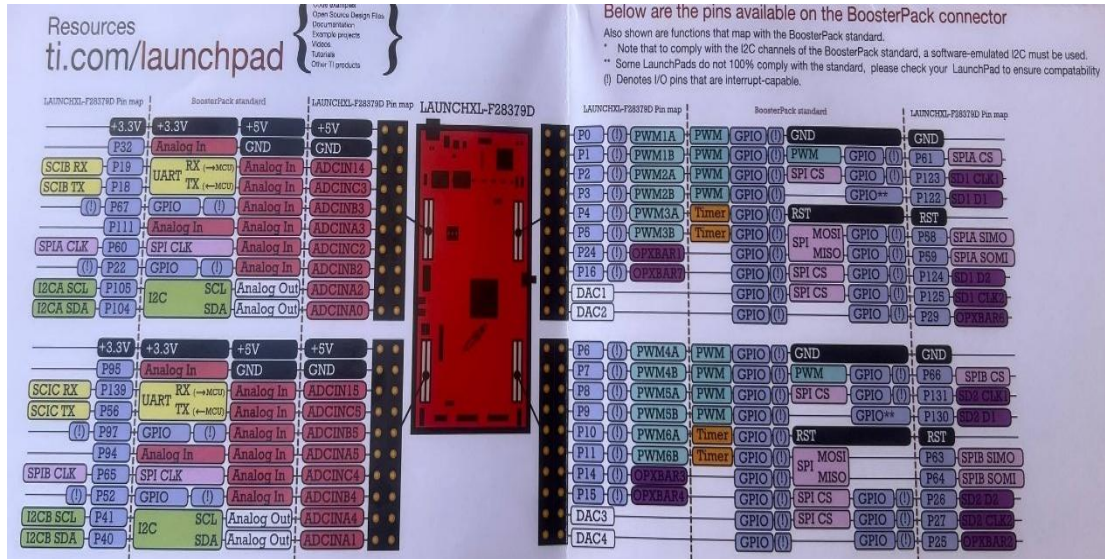


Figure .III.13:Command and Acquisition Interface (TMS320F28379D)

III.4.Ipmlementation results

Following the successful simulation and validation of the MPPT techniques in the MATLAB/Simulink environment, the next step consists of their real-time implementation on a hardware platform. The three MPPT methods, namely Perturb and Observe (P&O), Particle Swarm Optimization (PSO), and Fuzzy Logic Control (FLC), are embedded into the Texas Instruments TMS320F28379D microcontroller. The generated code is used to control the DC–DC boost converter by continuously adjusting the duty cycle, enabling the photovoltaic system to operate at its Maximum Power Point (MPP). This real-time implementation allows the performance of the different MPPT techniques to be evaluated and compared in terms of tracking accuracy, convergence speed, stability, and extracted power under varying environmental conditions.

III .4.1. Real-Time Implementation of the P&O MPPT Method

The Perturb and Observe (P&O) method was implemented in real time on the Texas Instruments TMS320F28379D microcontroller. The algorithm adjusts the duty cycle of the DC–DC boost converter according to the variations in the photovoltaic power, allowing the operating point to converge toward the Maximum Power Point (MPP) and maximize the extracted energy.

III.4.1.1. Low Irradiance Test



Figure .III.14: Experimental Investigation of the Designed System P&O MPPT Technique in low Irradiance

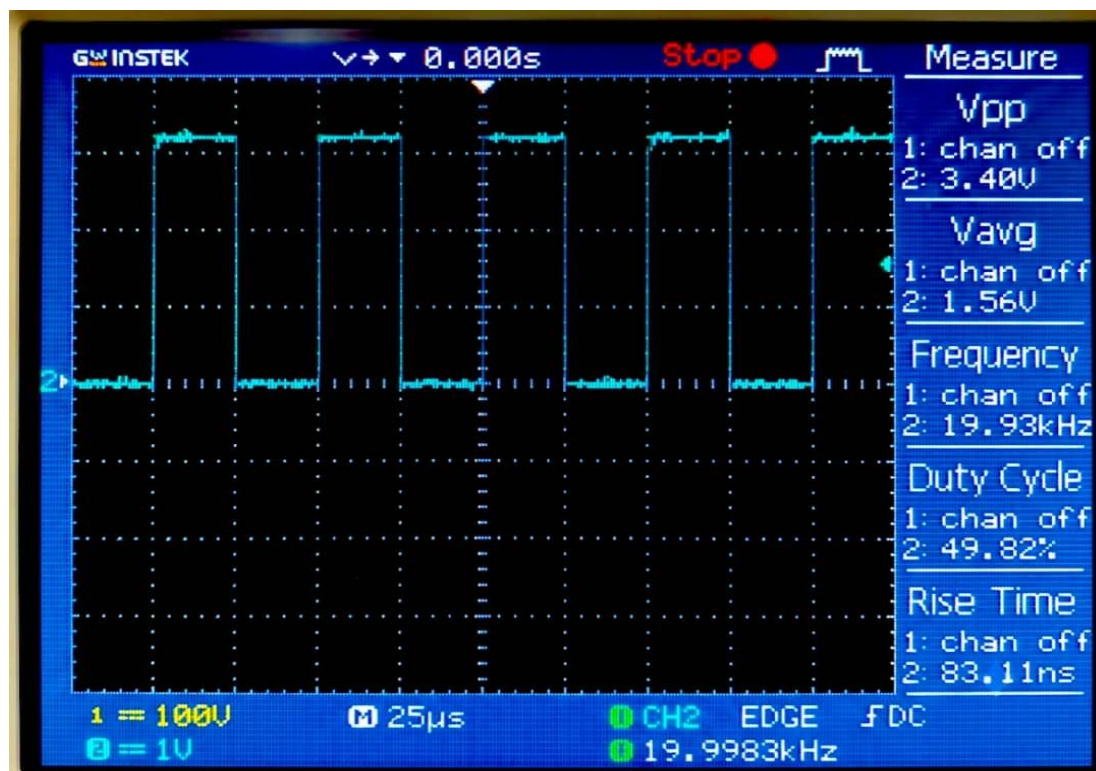
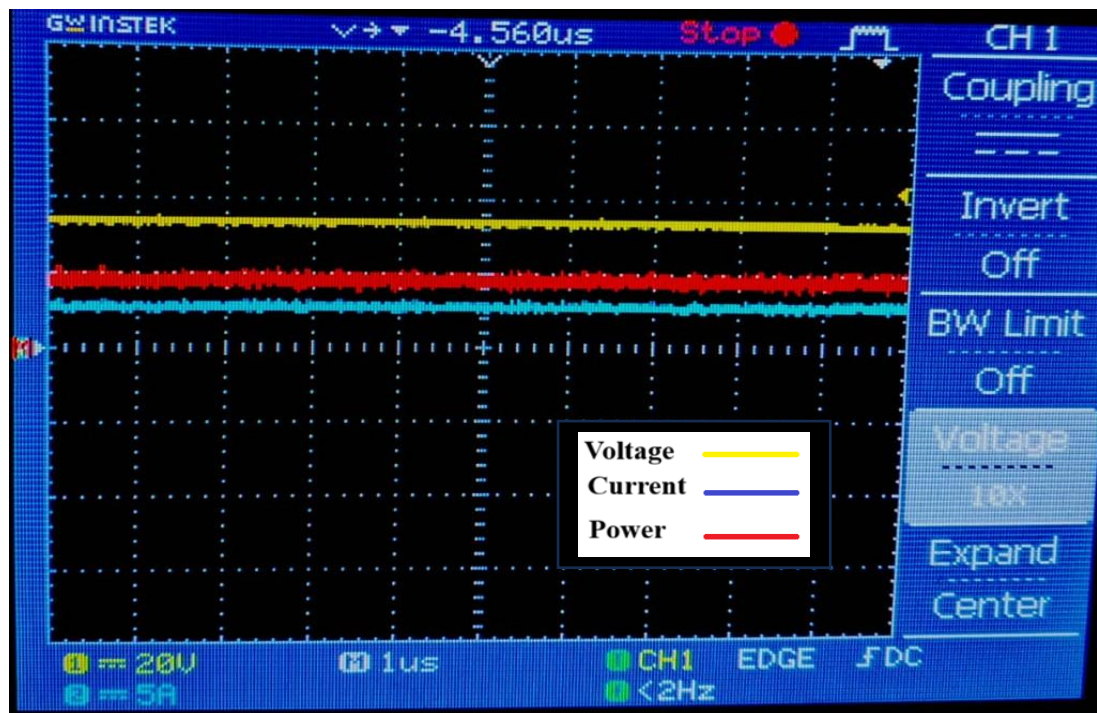
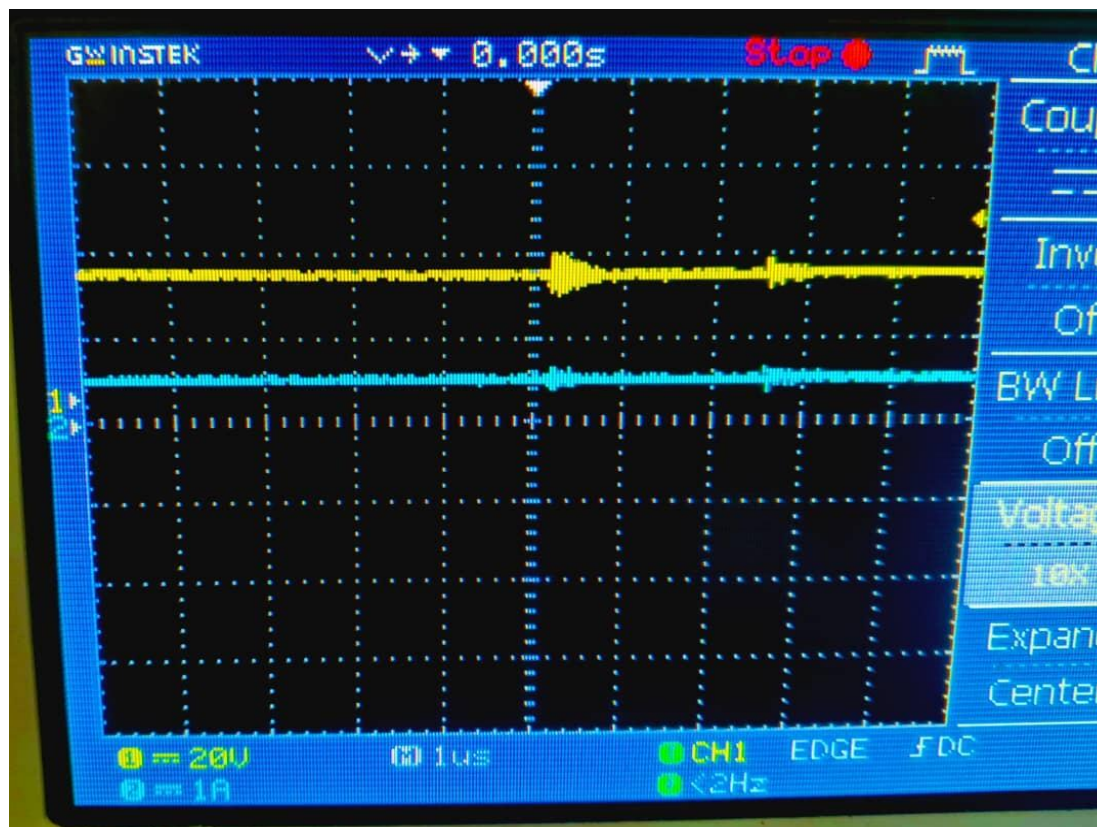


Figure .III.15: duty cycle



a) Voltage, Current and power of the PV panel



b) Output Voltage and Current of the Boost Converter

Figure .III.16:Boost Converter Input and Output Characteristics Under Low Irradiance

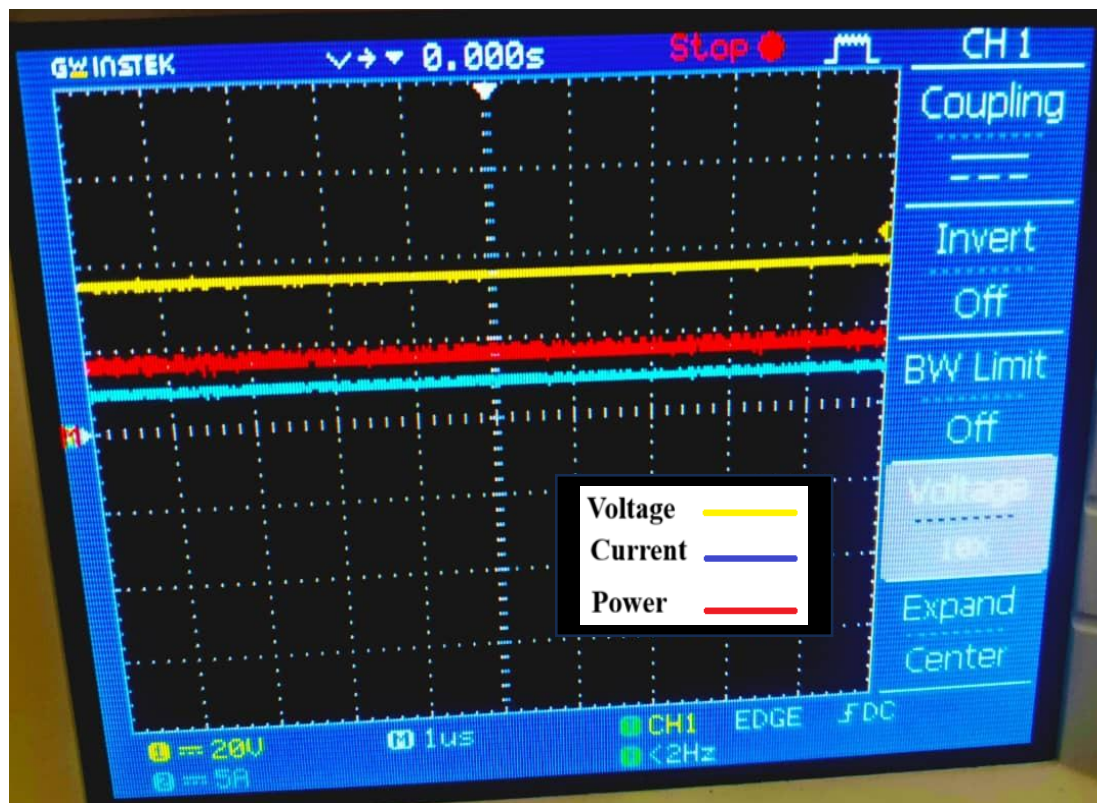
Tabel. III.4: Result low Irradiance

Panel voltage $V_{pv}(v)$	36.7 V
Panel current (A)	0.94 A
Panel power $P_{pv}(w)$	34.49 W
Boost output voltage $V_s(v)$	38.6 V
Boost output current $I_s(A)$	0.87 A

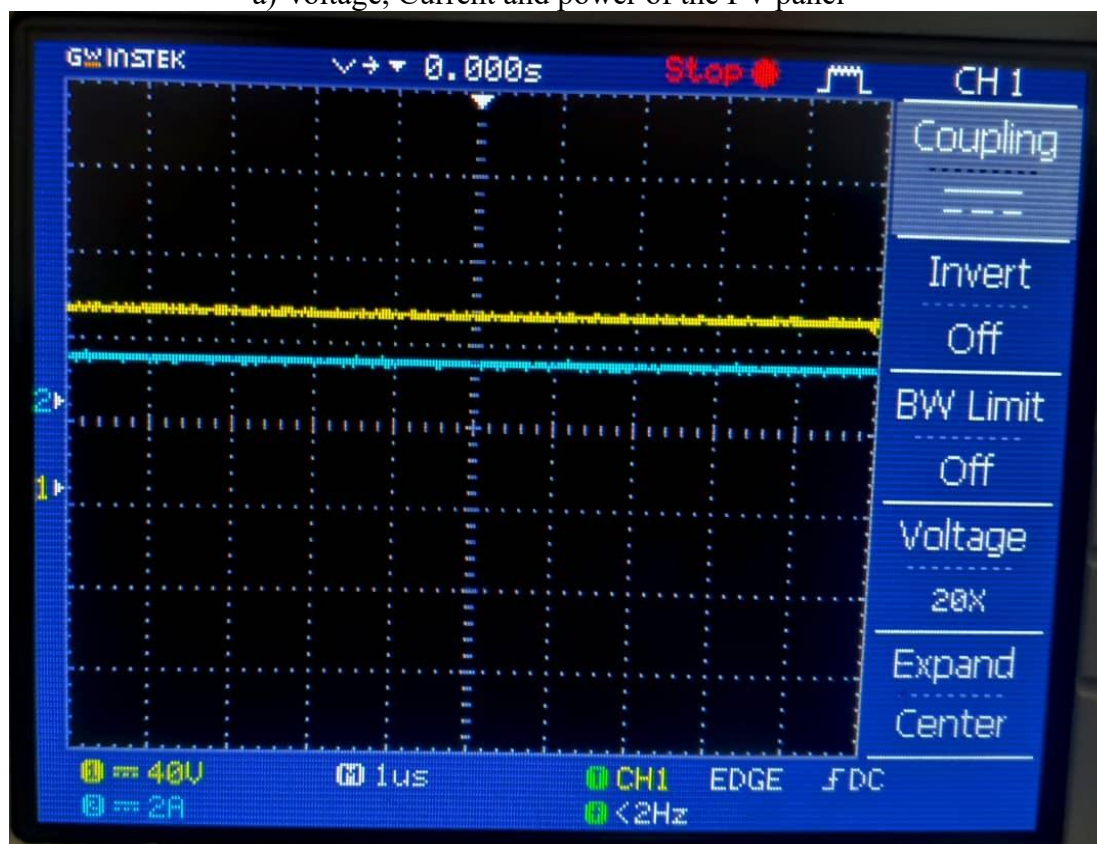
III.3.1.2.High Irradiance Test



Figure .III.17: Experimental Investigation of the Designed System P&O MPPT Technique in high Irradiance



a) Voltage, Current and power of the PV panel



b) Output Voltage and Current of the Boost Converter

Figure. III.18: Boost Converter Input and Output Characteristics Under hige Irradiance

Tabel .III.5: Result hige Irradiance

Panel voltage $V_{pv}(v)$	41.7
Panel current (A)	2.50
Panel power $P_{pv}(w)$	104.25
Boost output voltage $V_s(v)$	55.1
Boost output current $I_s(A)$	1.66

-Discussion

The experimental results in Figures 20 and 21 demonstrate the efficiency of the P&O algorithm in tracking the Maximum Power Point (MPP) under low and high solar irradiance conditions.

III.4.2. Fuzzy Logic Controller

After validating the effectiveness of the Fuzzy Logic Control (FLC) algorithm in the MATLAB/Simulink environment, the controller was implemented in real time using the TMS320F28379D to control the DC-DC Boost converter. The system dynamically adjusted the duty cycle to achieve fast and stable MPPT tracking while reducing oscillations under varying solar irradiation conditions.

III.4.2.1. High Irradiance Test

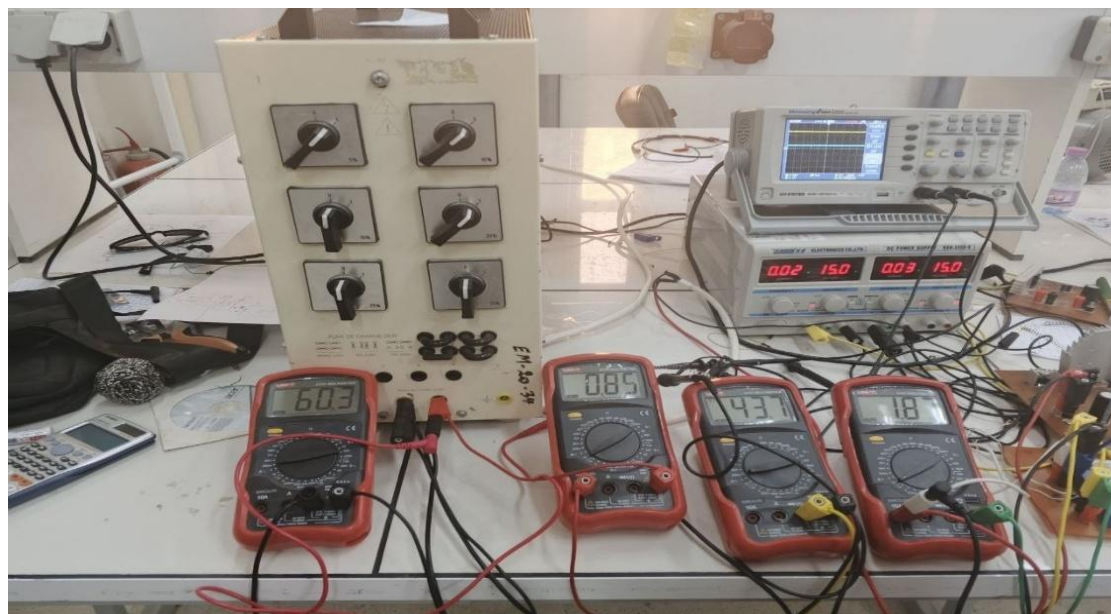


Figure .III.19: Experimental Investigation of the Designed System Fuzzy MPPT Technique in high Irradiance

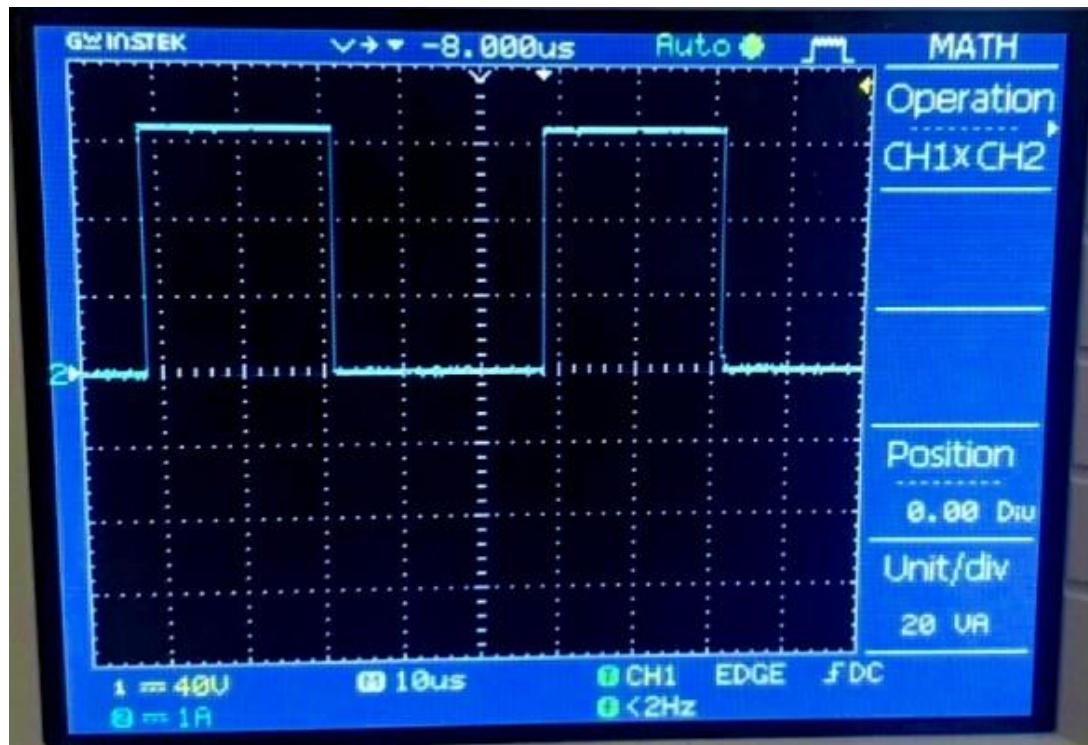
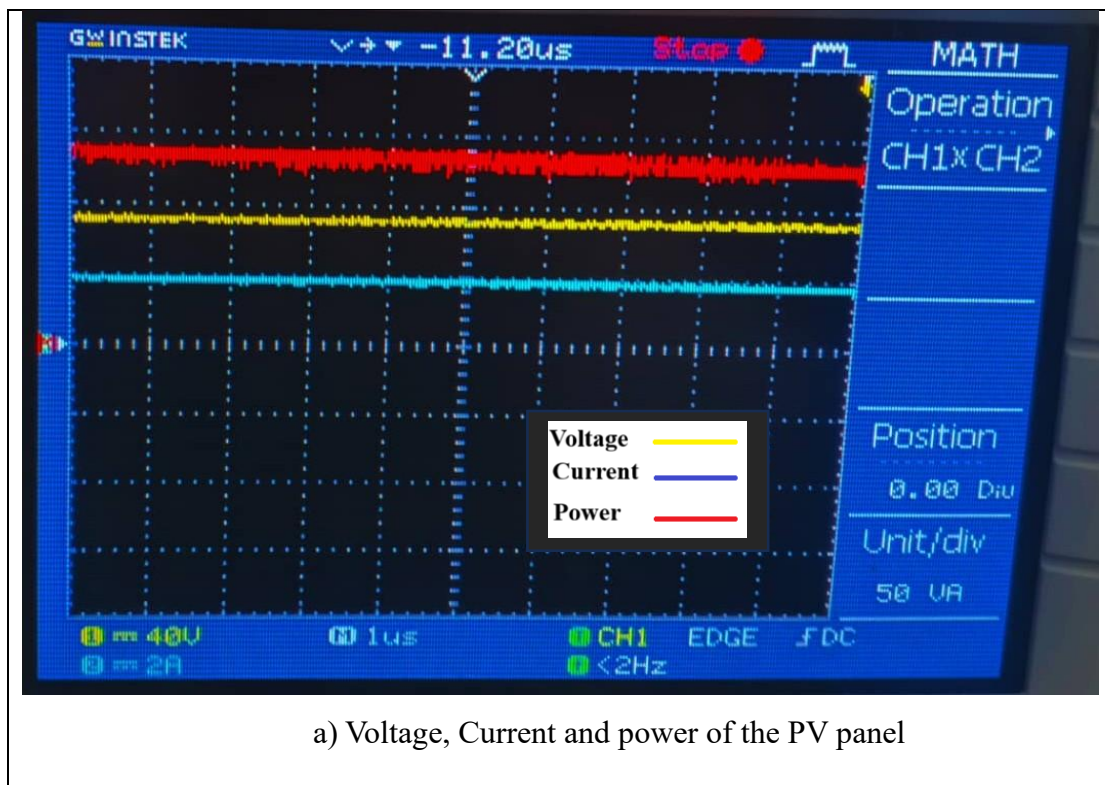


Figure .III.20: duty cycle



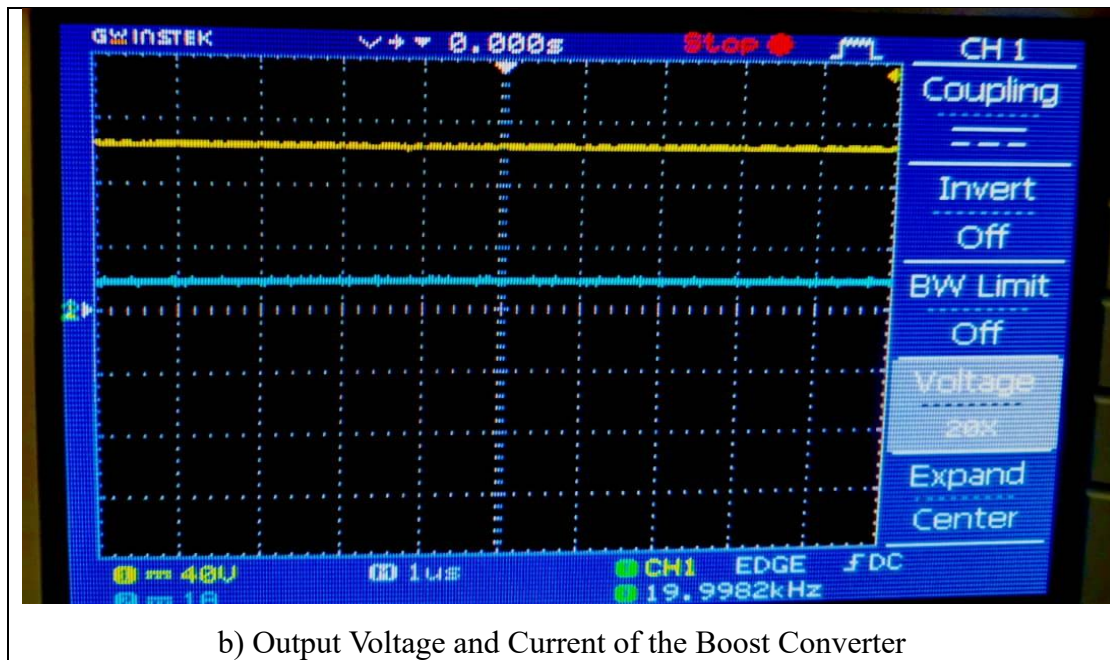


Figure .III.21: Boost Converter Input and Output Characteristics Under hige Irradiance

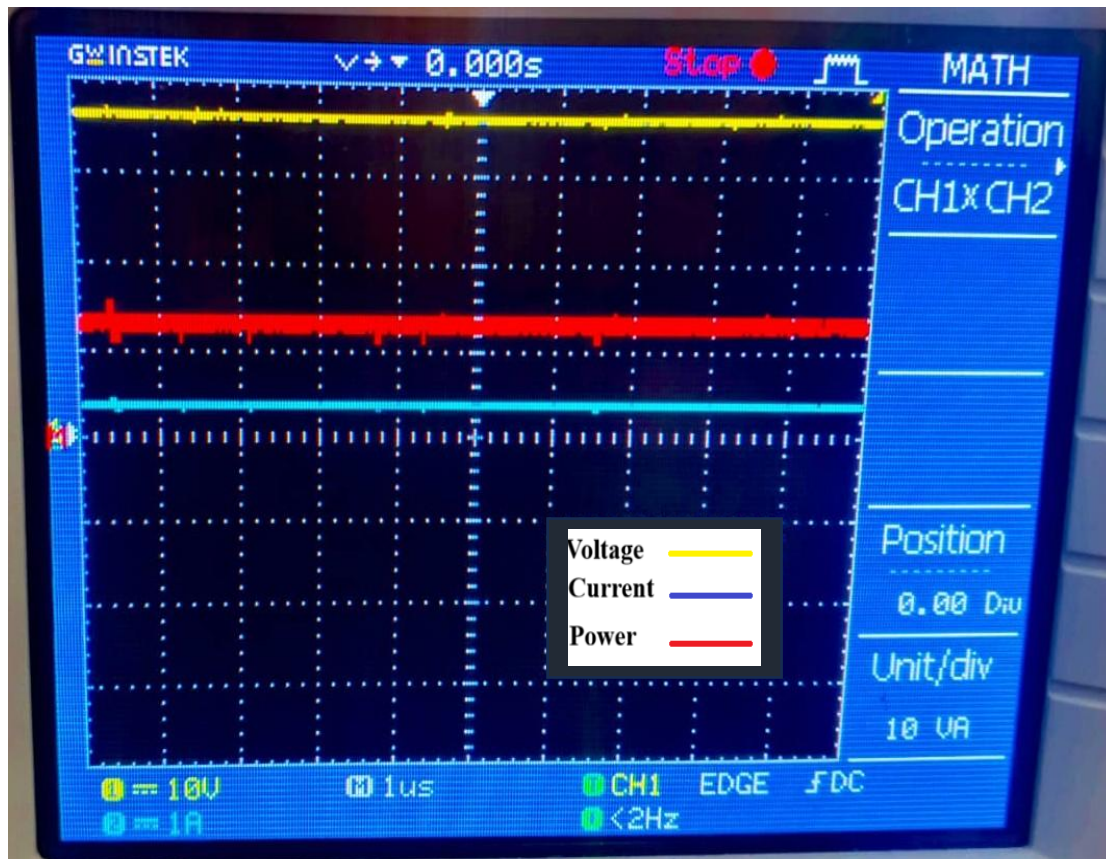
Tabel. III.6: Result hige Irradiance

Panel voltage $V_{pv}(v)$	43.7
Panel current (A)	1.87
Panel power $P_{pv}(w)$	81.719
Boost output voltage $V_s(v)$	60.3
Boost output current $I_s(A)$	0.85

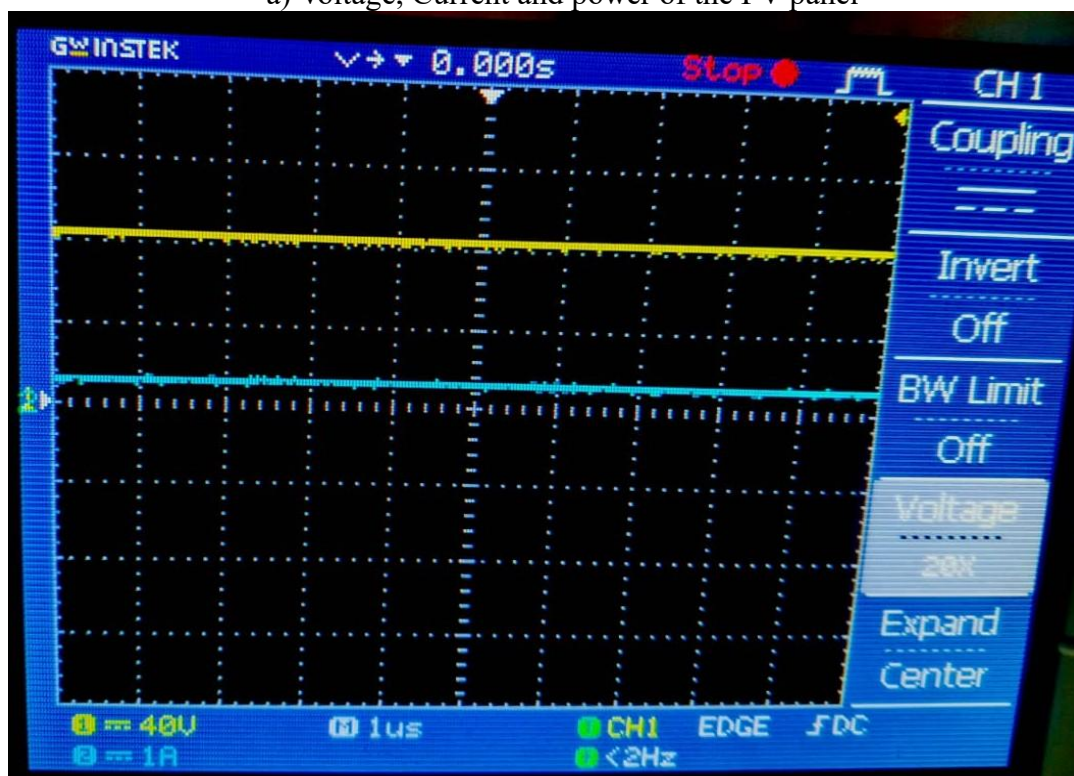
III.4.2.2 . Low Irradiance Test



Figure. III.22 Experimental Investigation of the Designed System FLC MPPT Technique in low Irradiance



a) Voltage, Current and power of the PV panel



b) Output Voltage and Current of the Boost Converter

Figure. III.23:Boost Converter Input and Output Characteristics Under Low

Irradiance

Tabel .III.7 : Result low Irradiance

Panel voltage $V_{pv}(v)$	45.5
Panel current (A)	0.57
Panel power $P_{pv}(w)$	25.937
Boost output voltage $V_s(v)$	34.8
Boost output current $I_s(A)$	0.42

- Discution

These practical results demonstrate the efficiency of the Fuzzy Logic Controller (FLC) in reducing oscillations around the Maximum Power Point (MPP) compared to conventional MPPT methods. The controller provides a faster and more stable response under changing operating conditions. As a result, the power losses are minimized and the overall power conversion efficiency of the Boost Converter is improved.

III.4.3. Particle Swarm Optimization

Following the validation of the Particle Swarm Optimization (PSO) algorithm through MATLAB/Simulink simulations, the next step consists of its real-time experimental implementation. The optimized control algorithm was converted into embedded code and deployed on the high-performance TMS320F28379D microcontroller. Thanks to its fast processing capabilities, the controller efficiently executes the PSO-based MPPT algorithm in real time. The implemented system ensures effective control of the DC–DC Boost converter while accurately tracking the maximum power point of the photovoltaic source. In addition, it rapidly responds to variations in solar irradiance and temperature. This experimental stage confirms the practicality, reliability, and effectiveness of the proposed PSO-based MPPT approach.

III.4.3.1. High irradiation Test



Figure III.24: Experimental Investigation of the Designed System (PSO)MPPT Technique in high Irradiance

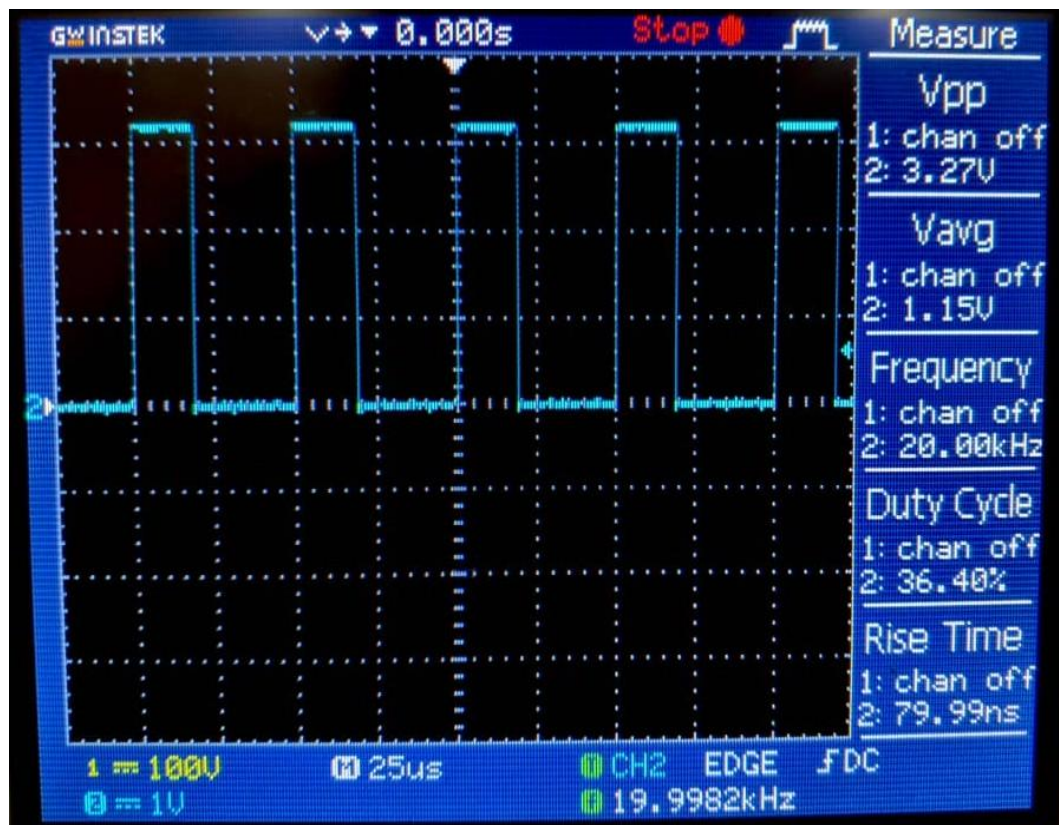
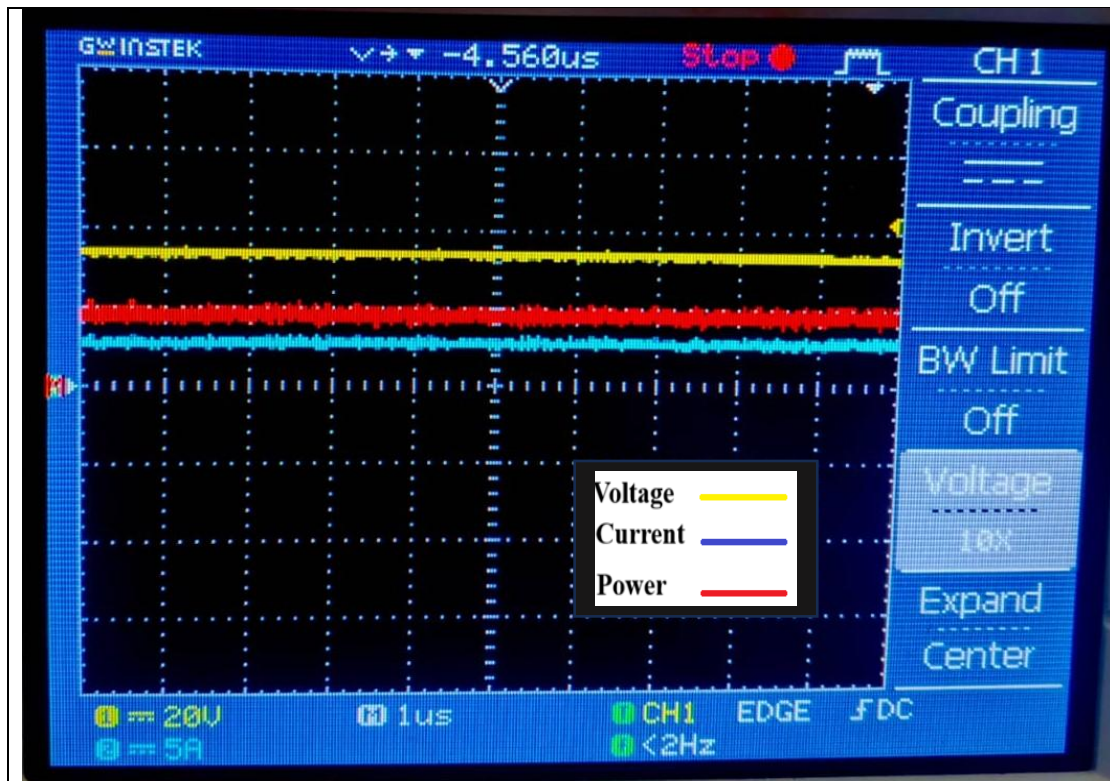
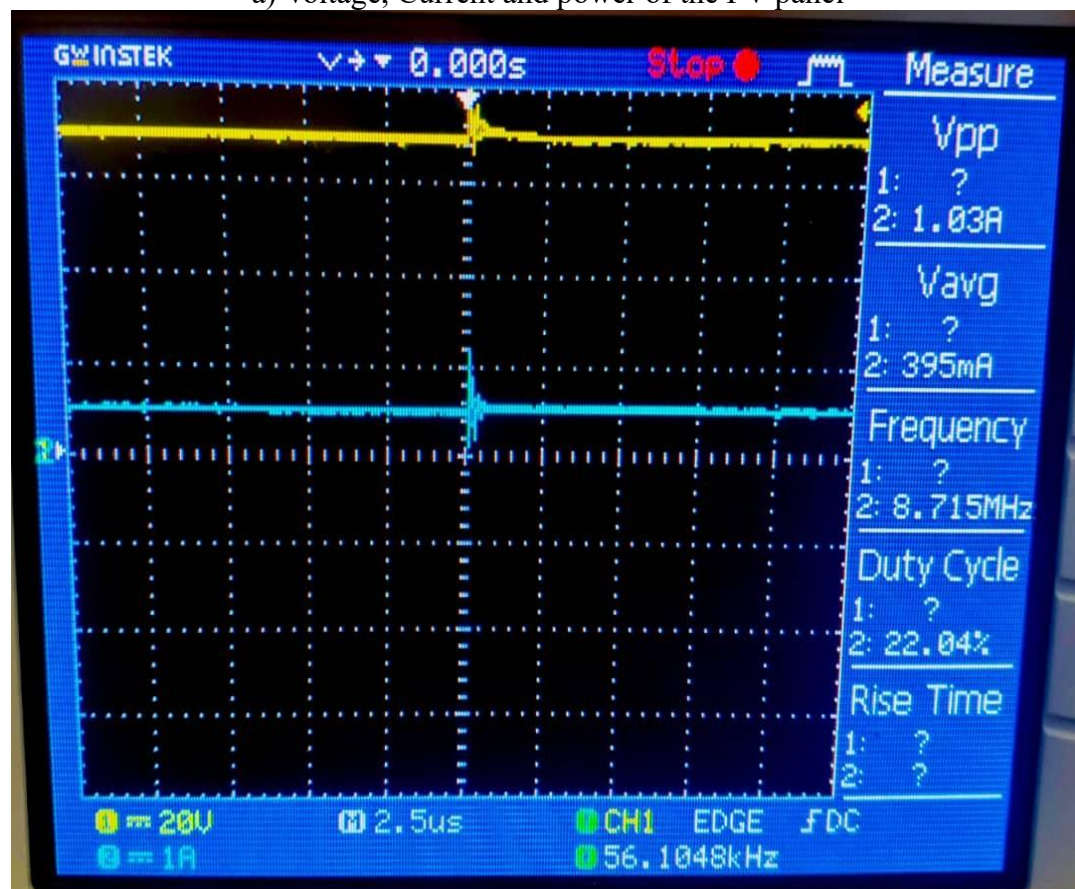


Figure III.25: duty cycle



a) Voltage, Current and power of the PV panel



b) Output Voltage and Current of the Boost Converter

Figure .III.26. Boost Converter Input and Output Characteristics Under hige Irradiance

Tabel .III.8 :Result hige Irradiance

Panel voltage $V_{pv}(v)$	38.3
Panel current (A)	3.12
Panel power $P_{pv}(w)$	119.5
Boost output voltage $V_s(v)$	71.4
Boost output current $I_s(A)$	0.87

III.4.3.2.Low irradiation Test

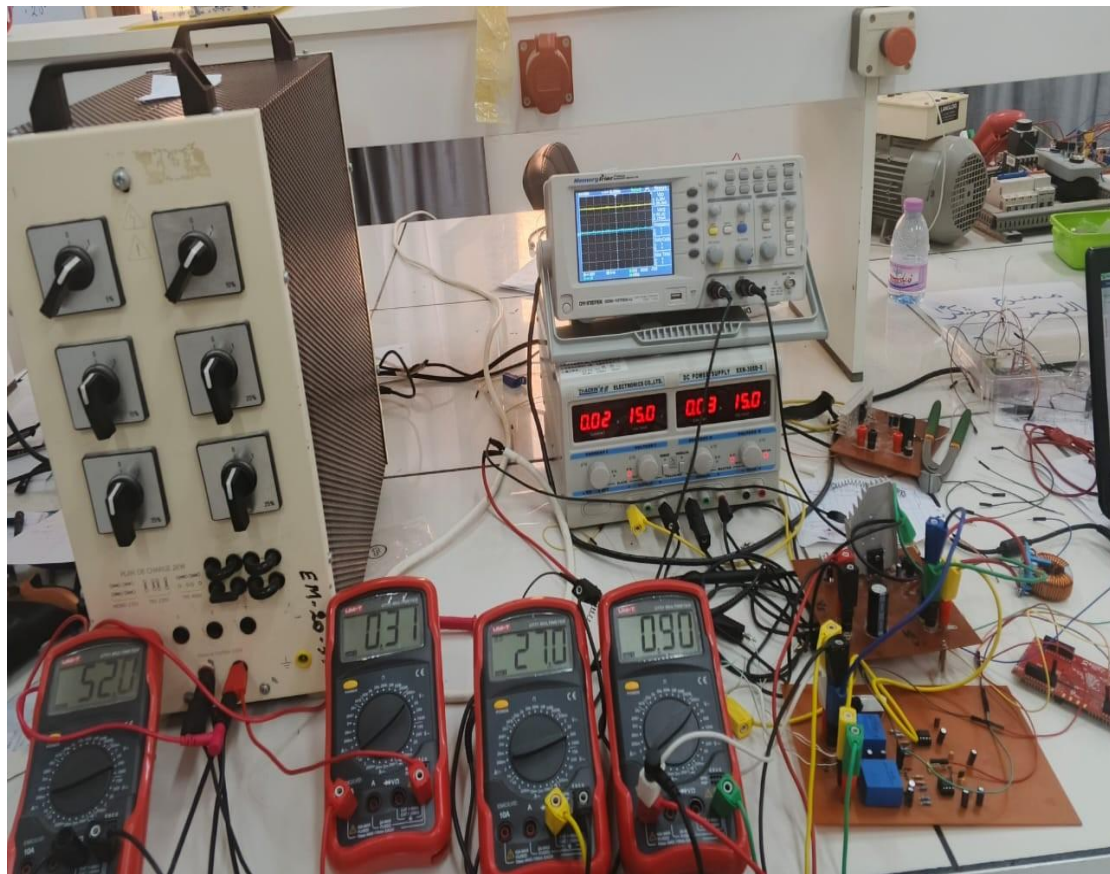
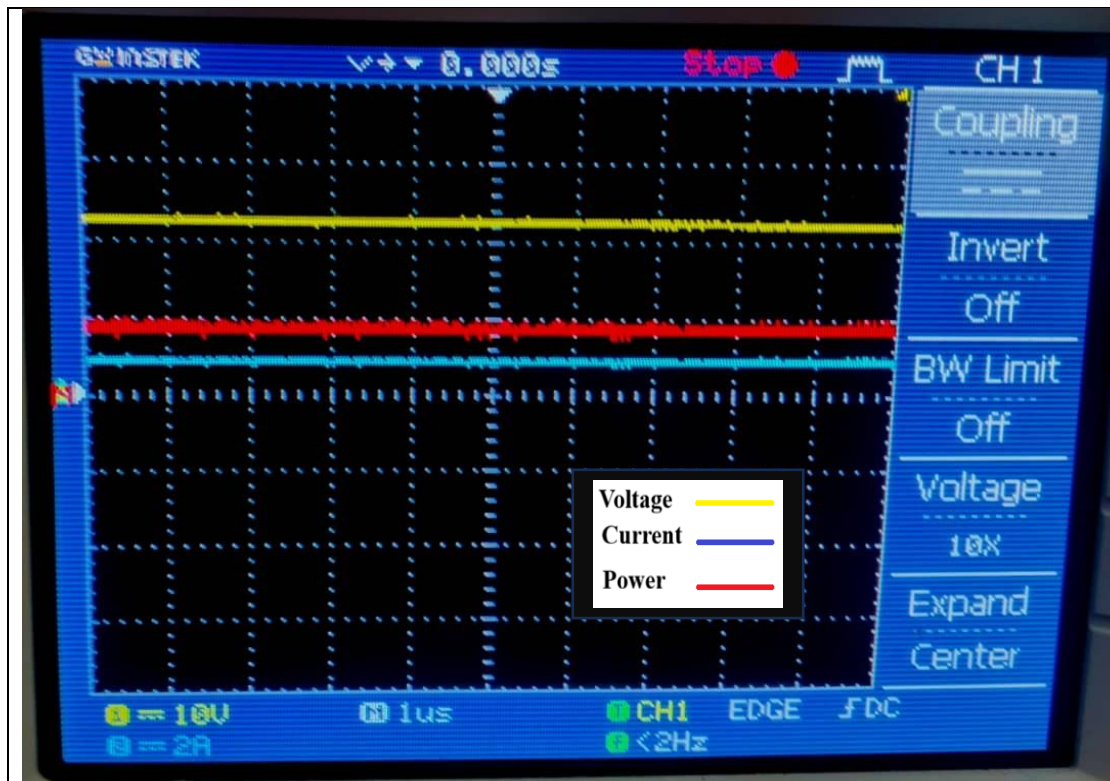
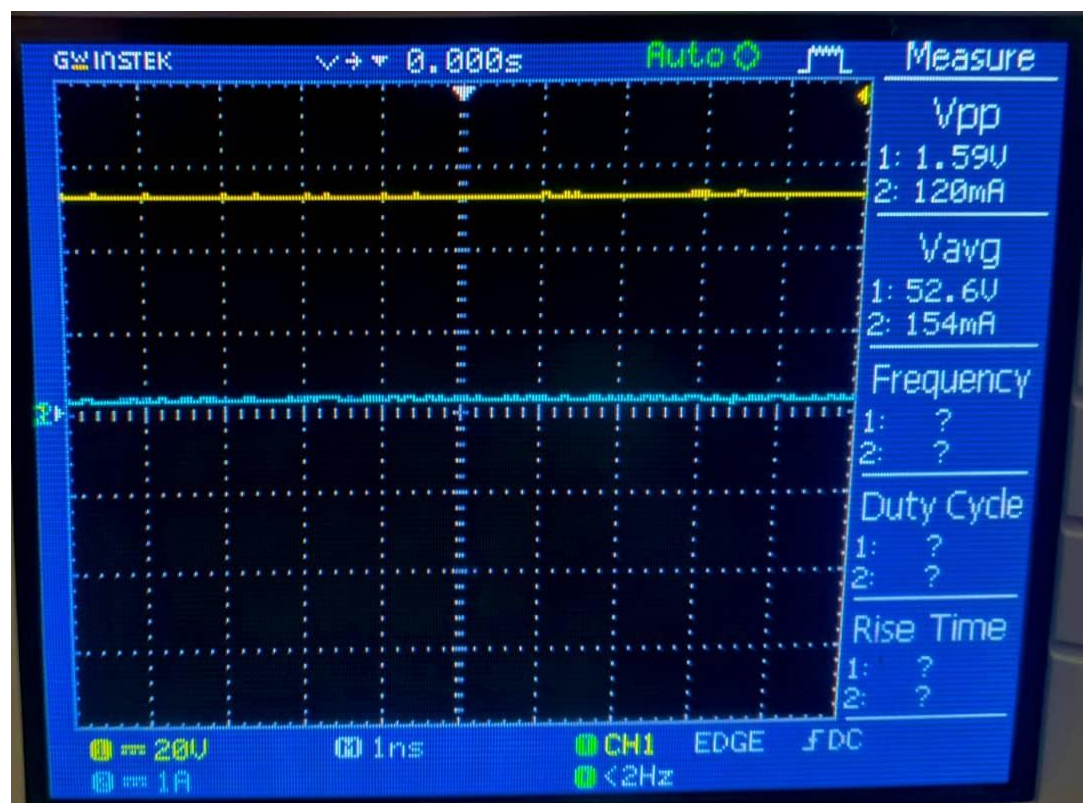


Figure. III.27: Experimental Investigation of the Designed System (PSO) MPPT Technique in low Irradiance



a) Voltage, Current and power of the PV panel



b) Output Voltage and Current of the Boost Converter

Figure .III.28: Boost Converter Input and Output Characteristics Under low Irradiance

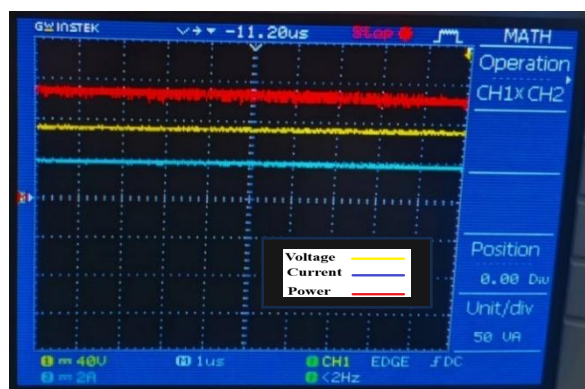
Tabel. III.9: Result low Irradiance

Panel voltage $V_{pv}(v)$	27
Panel current (A)	0.90
Panel power $P_{pv}(w)$	24.3
Boost output voltage $V_s(v)$	52.0
Boost output current $I_s(A)$	0.31

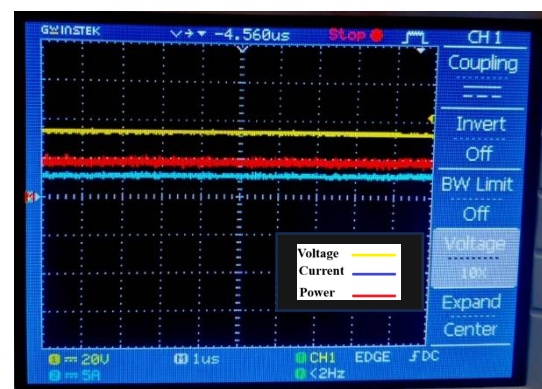
- Discution

These practical measurements demonstrate the efficiency of the PSO algorithm in the comprehensive elimination of Steady-State oscillations, ensuring high dynamic stability that increases the efficiency of the entire PV system in various weather conditions

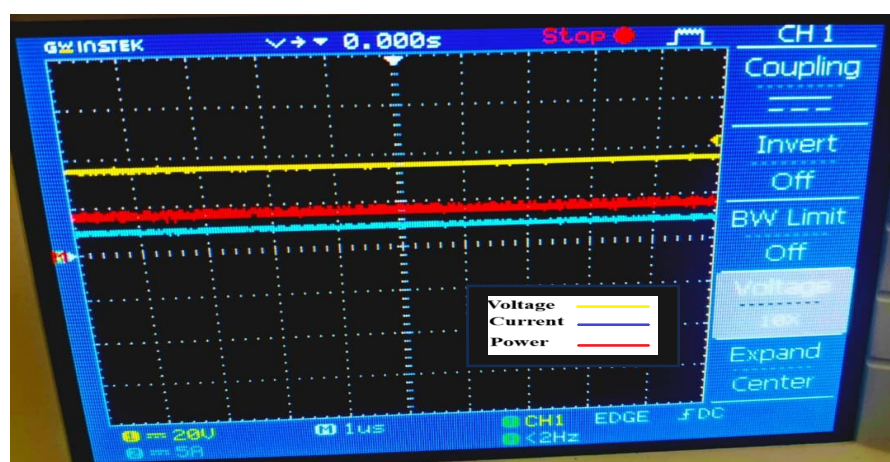
III. 5 .Comparative Analysis of MPPT Techniques



Fuzzy logic mppt



PSO mppt



P&O MPPT

Figure .III.29: Voltage, current and power of the PV panel of three methods

A comparative analysis of the MPPT techniques shows noticeable differences in their tracking performance. The Perturb and Observe (P&O) algorithm extracted approximately 104 W from the photovoltaic module. Although simple and easy to implement, the P&O method suffers from oscillations around the maximum power point, which may reduce the amount of harvested energy. In contrast, the Particle Swarm Optimization (PSO) technique achieved a higher extracted power of approximately 119 W, demonstrating superior tracking accuracy and a better ability to locate the maximum power point. Furthermore, PSO exhibited improved stability and reduced power fluctuations compared with the conventional P&O method. These results indicate that the PSO-based MPPT controller provides better energy extraction under the tested operating conditions.

The Fuzzy Logic Controller (FLC) achieved an extracted power of approximately 81 W. However, this result was obtained under different operating conditions, particularly with a different irradiance level and load. Therefore, a direct quantitative comparison between the FLC results and those obtained using the P&O and PSO algorithms cannot be considered fully representative. Nevertheless, the experimental waveforms showed that the FLC technique provided smoother operation and reduced oscillations compared with the conventional P&O method, confirming its effectiveness as an intelligent MPPT strategy.

III.6. Conclusion

In this chapter, we presented the design and simulation of the Boost Converter, followed by its practical implementation using the Texas Instruments LaunchPad digital control board. Then, we discussed the different components of the experimental system, such as the photovoltaic panel and the current and voltage sensors. Finally, practical tests were carried out on the photovoltaic system using the MPPT control algorithms (P&O, FLC, and PSO) under different solar irradiance levels (high and low). The experimental results obtained demonstrated that the designed system is capable of efficiently tracking and transferring the maximum power to the load under various climatic conditions.

GENERALE CONCLUSION

GENERALE CONCLUSION

This work investigated the modeling, simulation, and real-time implementation of a photovoltaic (PV) energy conversion system incorporating a Boost DC-DC converter and several Maximum Power Point Tracking (MPPT) techniques using the MATLAB/Simulink environment. The primary objective was to enhance the efficiency of the photovoltaic system by ensuring accurate and rapid tracking of the maximum power point under varying environmental conditions, particularly changes in solar irradiance and temperature.

A comprehensive model of the PV generator, the Boost converter, and the associated control algorithms was developed and analyzed. Three MPPT techniques were implemented and compared: the conventional Perturb and Observe (P&O) method, the Fuzzy Logic Controller (FLC), and the Particle Swarm Optimization (PSO) algorithm. The performance of these techniques was evaluated in terms of tracking speed, stability, oscillation reduction, and power extraction capability.

The simulation results demonstrated that all three methods were capable of tracking the maximum power point and improving the overall energy harvested from the photovoltaic system. However, the intelligent techniques, particularly the PSO algorithm, exhibited superior performance compared with the conventional P&O approach. PSO achieved faster convergence to the maximum power point, reduced steady-state oscillations, and improved system stability and efficiency under rapidly changing weather conditions. The FLC method also provided satisfactory performance and showed better robustness than the conventional method.

To validate the simulation results, the proposed MPPT algorithms were implemented in real time on a Texas Instruments C2000 digital signal controller. Experimental tests confirmed the feasibility of the developed control strategies and demonstrated their effectiveness in practical operating conditions. The real-time implementation showed good agreement with the simulation results and highlighted the capability of the C2000 platform to execute advanced MPPT algorithms efficiently.

Overall, this study confirms the importance of employing advanced MPPT techniques to maximize energy extraction and improve the performance of photovoltaic systems.

Future work may focus on the integration of hybrid or artificial intelligence-based optimization techniques, as well as the implementation and testing of these algorithms in larger-scale grid-connected photovoltaic installations.

References

- [1] BENMEDDAH, A., & LAIDI, K. (2025). Optimisation de l'algorithme MPPT pour un système photovoltaïque en intégrant de nouvelles techniques d'intelligence artificielle. Université de Bordj Bou Arreridj, Algérie
- [2] S. Naceur and K. Maziz, Commande MPPT d'un système photovoltaïque par les méthodes P&O et PSO, Master Thesis, Kasdi Merbah University, Ouargla, Algeria, 2024.
- [3] MOKHEFI, M. (2025). Design of an Intelligent MPPT Based on FLC Using a Photovoltaic System. Université d'Oran 1 Ahmed Ben Bella, Algérie
- [4] A. FERRAI, « Dimensionnement des Infrastructures Utilisant Diverses Sources Énergétiques Renouvelables Potentielles pour l'Alimentation Electrique d'un Village»; Mémoire de magister, Ecole Nationale Polytechnique, Alger, 2008.
- [5] IBRAHIM Tahraoui & AMINE Halil. Dimensionnement et Etude d'une installation Photovoltaïque pour une habitation domestique. Mémoire de master. Université de Tlemcen, Algérie, 2017
- [6] : K.Kassmi, M. Hamdaoui et F.Olivie, «Conception et modélisation d'un système photovoltaïque adapté par une commande MPPT analogique» Université Mohamed Premier, Faculté des Sciences, Département de physique, LEPAS, Oujda, Maroc. Revue des energies renouvelables, 451-462, 2007
- [7] N. Chandrasekaran, K. Thyagarajah, « Modeling and matlab simulation of pumping system using motor powered by solar system» European Journal of Scientific Research, 6-13, 2011
- [8] SLAMA Fateh. modelisation d'un Sys multi générateurs PV interconnectes au réseau électrique. magister en eth. ufasetif.
- [9] M. Krimi, le gisement solaire (présentation sur power point), Institut de formation en électricité et gaz (IFFEG), 13 mai Blida, Algérie.
- [10] M. Krimi, le gisement solaire (présentation sur power point), Institut de formation en électricité et gaz (IFFEG), 13 mai Blida, Algérie.
- [11] Yves Roulet-Ingénieur Environnement « différentes utilisations de l'énergie solaire et intégration des capteurs solaires » département des infrastructures service des bâtiments, monuments et archéologie, mai 2005
- [12] J. A. Duffie, W. A. Beckman, and N. Blair, Solar Engineering of Thermal Processes, Photovoltaics and Wind, 5th ed., Wiley, 2020.
- [13] O. Boukli-Hacene, "Design and implementation of a photovoltaic generator equipped with an MPPT converter for improved energy management," Master's Thesis, University of Abou Bakr Belkaid-Tlemcen, 2011

- [14] C. Fatima, Étude des cellules photovoltaïques en silicium, Mémoire de fin d'études, Université de Naâma, Algérie, 2024.
- [15] O. Boukli-Hacene, "Design and implementation of a photovoltaic generator equipped with an MPPT converter for improved energy management," Master's Thesis, University of Abou Bakr Belkaid-Tlemcen, 2011
- [16] Cuong Hung Tran, "Improvements to a solar energy to electricity conversion chain for applications in developing countries," [PhD Thesis], University of Reims Champagne-Ardenne, Doctoral School of Sciences, Technology, and Health; 2019.
- [17] Photovoltaïque Electricité solaire, document délivré par l'association suisse des professionnels de l'énergie solaire.
- [18] Maouedj Rachid, "Application de l'énergie photovoltaïque au pompage hydraulique sur les sites de Tlemcen et de Bouzareah", Mémoire De Magister ,2005.
- [19] N. Oleksiy, "Simulation, fabrication et analyse de cellules photovoltaïques à contacts arrières interdigités," Institut national des sciences appliquées de Lyon, 2005.
- [20] R. Merahi and R. Chenni, Nouvelles architectures distribuées de gestion et de conversion de l'énergie pour les applications photovoltaïques. Ph Dthesis, Université Frères Mentouri Constantine, 2018.
- [21] G. R. Tapsoba, Maximisation du transfert de l'énergie d'un champ photovoltaïque tenant compte du phénomène d'ombrage partiel : connexion réseau électrique. PhD thesis, École de technologie supérieure, 2019.
- [22] T. T. Guingane, Z. Koalaga, E. Simonguy, F. Zougmore, and D. Bonkougou, "Modélisation et simulation d'un champ photovoltaïque utilisant un convertisseur élévateur de tension (boost) avec le logiciel matlab/simulink," 2016.
- [23] MOULFI Mohamed et BEKADA BENCHAIB Oussama. « Impact CEM des liaisons d'interconnexions dans un système électrique de 100w à base d'une RSIL et un convertisseur dc /dc de type Buck ». Mémoire de master. Département de Génie électrique. Faculté de technologie. Université Belhadj Bouchaib d'Ain-Temouchent
- [24] CHOUIKHI Wassila Faiza. « Réalisation d'une commande Buck-Boost pour PV ». Mémoire de master. Département de Génie électrique et électronique (GEE). Faculté de technologie. Université Aboubakr Belkaid – Tlemcen.
- [25] BENKASSI, Fatima Zohra, et SELLAOUI, Assia. Modélisation dynamique et analyse des convertisseurs DC-DC pour applications en énergies renouvelables. Mémoire de Master Académique en Électrotechnique (Spécialité: Réseaux électriques), Université de Guelma, 2020.
- [26] BOUALEM, DENDIB, "Technique conventionnelles et avancée de poursuite MPPT pour des applications photovoltaïque : étude comparative.", Université Ferhat Abbes-Sétif Mémoire de Magister, Département d'électronique, 2007

- [27] Florida Solar Energy Center. (n.d.). Types of PV Systems. University of Central Florida.
- [28] S. Bensalem, Étude et dimensionnement d'un système photovoltaïque autonome, Mémoire de Master, Université d'Alger, 2019
- [29] A. Hamidouche, Conception d'un système photovoltaïque hybride autonome, Mémoire Master, Université de Constantine, 2020 .
- [30] L. Guo, Z. Meng, Y. Sun, and L. Wang, "Parameter identification and sensitivity analysis of solar cell models with cat swarm optimization algorithm," Energy conversion and management, vol. 108, pp. 520-528, 2016
- [31] TANSAOUT, Mahdia et KHEMMAR, Silia. Modélisation et simulation d'un panneau photovoltaïque sous MATLAB-SIMULINK. Mémoire de Fin d'Etudes de Master Académique, Spécialité : Matériaux et Dispositifs Electroniques et Photovoltaïques, Université Mouloud Mammeri de Tizi ousou, 2016
- [32] AISSAOUI, N. E. H., & KEDJEDJA, N. (2012). Modélisation et Simulation du Générateur Photovoltaïque (Mémoire de Master Académique, Option: Commande des machines électriques). Université 8 Mai 1945 - Guelma, Algérie
- [33] BOUNOUR, Azeddine & BOUTI, Yahia. (2021). Etude par simulation d'un système photovoltaïque avec stockage. Mémoire de Master en Electrotechnique, Spécialité: electrotechnique industrielle. Département d'Electrotechnique, Faculté des Sciences de l'ingéniorat, Université Badji Mokhtar – Annaba
- [34] FELLOUAH, S., & MESBAHI, S. (2015). ETUDE D'UN SYSTEME PHOTOVOLTAIQUE CONNECTE AU RESEAU (Mémoire de Master Académique). Université Mouloud Mammeri de Tizi-Ouzou, Algérie.
- [35] FELLOUAH, S., & MESBAHI, S. (2015). ETUDE D'UN SYSTEME PHOTOVOLTAIQUE CONNECTE AU RESEAU (Mémoire de Master Académique). Université Mouloud Mammeri de Tizi-Ouzou, Algérie
- [36] Advanced Control of Grid-Connected High-Power Converters and Industrial Applications
- [37] Benkassis, F. Z., & Sellaoui, A. (2020). Modélisation dynamique et analyse des convertisseurs DC-DC pour applications en énergies renouvelables (Mémoire de Master Académique en Électrotechnique, Spécialité : Réseaux électriques).

Département de Génie Electrotechnique et Automatique, Faculté des Sciences et de la Technologie, Université 8 Mai 1945 - Guelma, Algérie

[38] B. Abdelkader"" Modélisation et Diagnostic d'un Onduleur Triphasé par l'Approche Bond Graph ""Mémoire de Magister UNIVERSITE FERHAT ABBAS DE SETIF 02/12/2009.

[39] Power Electronics and Control Techniques for Maximum Energy Harvesting in Photovoltaic Systems, Boca Raton, FL, USA: CRC Press, 2013

[40] Sedrati Youcef et Nouar Hatem, *Implémentation de l'algorithme P&O pour un système photovoltaïque*, Mémoire de Master Académique, Département d'électronique et communication 2015/2016

[41] H. Rezzouk, « Simulation et implémentation d'algorithmes de recherche du point de maximum de puissance pour un système PV sur un circuit FPGA », Mémoire de Magister, Université de Jijel 2010

[42] H. Rezzouk, « Simulation et implémentation d'algorithmes de recherche du point de maximum de puissance pour un système PV sur un circuit FPGA », Mémoire de Magister, Université de Jijel 2010.

[43] V. Boitier, P. Maussion, C. CABAL, ,,,Recherche du maximum de puissance sur les générateurs photovoltaïques"", université de Toulouse, revue 3E.I, N°54, pp 90-96, septembre 2008

[44] Yassine Lasmi ,,"Optimisation de la poursuite du piont de puissance maximale (MPPT) d'un système photovoltaïque par techniques intelligentes,,", Mémoire de Magister Université Setif ,09/12/2013.

[45] BOUZELHA, Lyazid, Méthode de l'intelligence artificielle (floue) appliquée aux panneaux photovoltaïques, Mémoire de Master Académique, Spécialité Automatique et Système, Département d'Automatique, Faculté de Génie Électrique et d'Informatique, Université Mouloud Mammeri de Tizi-Ouzou, 2018

[46] Harkati, S., Haddi, M., & Morso, A. (2020). La commande MPPT-floue d'un générateur photovoltaïque [Mémoire de Master inédit]. Département de Technologie, Institut des Sciences et Technologies, Centre Universitaire de Naâma Université de Mascara, Algérie.

- [47] Wassila Issaadi "Control of a photovoltaic system by fuzzy logic, Comparative studies with conventional controls: results, improvements and perspectives" Int. J. Intelligent Engineering Informatics, Vol. 5, No. 3, 2017
- [48] N. Setyawan, E. A. Hakim, and Z. Zulfatman, "SIGNATURE PSO: MODIFIED PARTICLE SWARM OPTIMIZATION DENGAN FUZZY SIGNATURE DAN IMPLEMENTASI PADA OPTIMALISASI KENDALI LQR," MULTITEK INDONESIA.
- [49] LEM Components, "Voltage Transducer LV 25-P Datasheet," Geneva, Switzerland, Pub. No. 981125/14. Available: www.lem.com [Accessed: Jun. 5, 2026]
- [50] LEM Components. (1999). Current Transducer LA 25-NP/SP14 (Datasheet). Retrieved from LEM website.
- [51] Texas Instruments. (2025). TL08xx FET-Input Operational Amplifiers Datasheet (Literature No. SLOS081O). Retrieved from Texas Instruments website.
- [52] UTC, "25N06: N-Channel Enhancement Mode Power MOS Transistor Datasheet," Unisonic Technologies Co., Ltd, Vol.
- [53] Texas Instruments, "LAUNCHXL-F28379D Overview User's Guide," Lit. No. SPRUI77C, August 2016, Revised March 2019. [Online].