



People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University of Echahid Hamma Lakhdar - El Oued



Faculty of Technology
Department of Electrical Engineering

Dissertation

ACADEMIC MASTER

Domain: Science and Technology

Division: Electrical Engineering

Specialty: Electrical Networks

Presented by:

Ouahida MESBAHI

Entitled:

**Study of Different MPPT Algorithm for PV
Photovoltaic system
(Cuckoo Search and Kalman Filter)**

Publicly defended in: 28/05 /2025

Board of Examiners:

Dr. Said CHIKHA

Chairman

Dr. Ridha KECHIDA

Supervisor

Dr. Abdelmalek GACEM.

Examiner

Academic Year: 2024/2025



Acknowledgments

First and foremost, I would like to thank God “Allah” the Most Gracious and the Most Merciful, for blessing me with knowledge and giving me strength, courage, patience, and serenity during all these years of study.

I would also like to express my sincere appreciation to all those who contributed to the successful completion of this work. All thanks and appreciation to my honorable supervisor: Dr. KECHIDA Ridha for his unwavering support, guidance, and encouragement have been invaluable during the course of my project. His extensive expertise and diligent efforts have significantly enriched my academic journey.

Last but not the least, I am profoundly thankful to my parents. Their prayers, guidance, and unwavering support have been instrumental in my education. Their inspiration and encouragement have been a beacon of light, guiding me through the challenges and triumphs of my academic pursuit.



ملخص

تهدف هذه الدراسة إلى تحسين أداء وكفاءة أنظمة الطاقة الشمسية الكهروضوئية من خلال معالجة التحديات التشغيلية الناجمة عن الأعطال وتقلبات الظروف البيئية. تركز البحث على تحليل وتنفيذ خوارزميات متقدمة لتتبع نقطة الطاقة القصوى (MPPT)، مع محاكاة أدائها في بيئة ماتلاب.

أظهرت النتائج تفوق الخوارزمية مرشح كالمان (KF) والتوصيل التدريجي (INC) من حيث سرعة الاستجابة الديناميكية، ودقة التتبع، والاستقرار تحت ظروف الإشعاع ودرجة الحرارة المتغيرة بسرعة. في المقابل، أظهرت الخوارزمية الاضطراب والملاحظة وخوارزمية التحسين الذكي البحث عن الوقواق (CS) سرعة تقارب أبطأ، لكنها حافظت على فعاليتها في الاقتراب من نقاط الطاقة المثلى العالمية، خاصة في السيناريوهات المعقدة.

تستنتج الدراسة أن الجمع بين دقة الخوارزميات الذكية وسرعة استجابة الخوارزميات التقليدية يمثل مسارًا واعدًا للتطوير المستقبلي. كما تؤكد على أهمية دعم البحث في الخوارزميات الهجينة لتحقيق توازن أمثل بين الأداء والكفاءة، مما يساهم في تعزيز موثوقية وإنتاجية أنظمة الطاقة الشمسية كركن أساسي في الانتقال نحو مصادر الطاقة النظيفة والمستدامة.

Abstract

This study aims to enhance the performance and efficiency of photovoltaic (PV) systems by addressing operational challenges caused by faults and environmental fluctuations. The research focuses on analyzing and implementing advanced Maximum Power Point Tracking (MPPT) algorithms, with their performance simulated in a MATLAB environment.

The results demonstrated the superiority of advanced algorithms such as the **Kalman Filter (KF)** and **Incremental Conductance (INC)** in terms of dynamic response speed, tracking accuracy, and stability under rapidly changing irradiance and temperature conditions. In contrast, traditional algorithms like **Perturb and Observe (P&O)** and the intelligent optimization technique **Cuckoo Search (CS)** exhibited slower convergence rates but maintained effectiveness in approaching global optimal power points, particularly in complex scenarios.

The study concludes that combining the precision of intelligent algorithms with the rapid response of traditional ones represents a promising path for future development. It also emphasizes the importance of supporting research into hybrid algorithms to achieve an optimal balance between performance and efficiency, thereby contributing to the enhanced reliability and productivity of solar energy systems as a cornerstone in the transition to clean and sustainable energy sources.

LISTE DES TABLEAUX

Title of tableaux	Page
Table (I.1). Characteristics of the Sun Power SPR-76R-BLK-U module.	14
Table (II.1). The response of the control system for each case of P&O algorithm.	25
Table (II.2). PV model characteristics.	27

Figure Titre	Page
Figure (I.1). Solar radiation potential in Algeria	3
Figure (I.2). Solar cell production by region in globe	3
Figure (I.3). Average solar irradiance	4
Figure (I.4). Hydraulic power plant	5
Figure (I.5). Geothermal energy	6
Figure (I.6). Biomass power plant	6
Figure (I.7). Wind turbine	7
Figure (I.8). A solar installation	7
Figure (I.9). Monocrystalline	8
Figure (I.10). Polycrystalline	8
Figure (I.11). Amorphes	8
Figure (I.12). PV panels in series	9
Figure (I.13). PV panels in parallel	9
Figure (I.14). PV panels in series-parallel	10
Figure (I.15). On-Grid photovoltaic system	10
Figure (I.16). Hybrid photovoltaic system	11
Figure (I.17). Off-grid photovoltaic system	11
Figure (I.18). The constitution of a photovoltaic array	12
Figure (I.19). I-V characteristic for ns PV cells	12
Figure (I.20). I-V characteristic for np PV cells	12
Figure (I.21). Bypass diode and blocking diode	13
Figure (I.22). Characteristics of a PV for different temperatures and irradiations conditions.	15
Figure (I.23). Common types of MPPT methods for PV systems	16
Figure (II.1). Equivalent circuit of solar cell ideal (a) and (b) practical	18
Figure (II.2). General (I-V) curve of PV cell	19
Figure (II.3). PV -load connection via power stage	20
Figure (II.4). Buck converter	21

Figure (II.5). Boost converter	21
Figure (II.6). Waveform of a DC-DC Boost converter	21
Figure (II.7). Boost converter during on time	22
Figure (II.8). Boost converter during Off time	22
Figure (II.9). Principle of MPPT control	24
Figure (II.10). Different possible cases for the functioning of P&O Algorithm	25
Figure (II.11). Flowchart of P&O MPPT method	26
Figure (II.12). Flowchart of INC MPPT method	26
Figure (II.13). I–V and P–V curves for PV array under various irradiance conditions	27
Figure (II.14). Simulation results of the PV at (T=25°C, E=1000W/m ²)	28
Figure (II.15). Signal builder for variable irradiance and constant temperature	29
Figure (II.16). Simulation results of the PV for variable irradiance and (T=25°C)	30
Figure (II.17). Simulation results of the PV for variable irradiance and (T=25°C)	31
Figure (III.1). MPPT algorithm using the Kalman Filter	35
Figure (III.2). PV (P – V) curve	35
Figure (III.3). PV (P – V) curve	36
Figure (III.4). Flowchart of the KF MPPT method	37
Figure (III.5). The number of available host nests is fixed	37
Figure (III.6). Flowchart of variable step size CS MPPT method	40
Figure (III.7). Signal Builder for variable irradiation and constant temperature	40
Figure (III.8). Simulation results of the PV for variable irradiance and (T=25°C)	41
Figure (III.9). Simulation results of the PV for variable irradiance and (T=25°C)	42
Figure (III.10). Block diagram of a photovoltaic system by the MPPT (P&O- INC- KF- CS)	43
Figure (III.11). Comparison different MPPT techniques	45
Figure (III.12). Comparison methods for the different condition	47

Title	Page
Acknowledgements	
Declaration	
Nomenclature	
List of figures	
List of tables	
Table of contents	
General Introduction	1
Chapter I. Introduction Solar Photovoltaic System	
I.1. Introduction	2
I.2. Historical Background	2
I.3. Solar energy in Algeria	3
I.4. Introduction of Solar Energy	3
I.5. Overview of Renewable Energies	4
I.5.1. Hydraulic Energy	5
I.5.2. Geothermal Energy	5
I.5.3. Biomass Energy	6
I.5.4. Wind Energy	6
I.5.5. Solar Energy	7
I.6. Types of Photovoltaic Cells	8
I.6.1. Monocrystalline Silicon Cells	8
I.6.2. Polycrystalline Silicon Cell	8
I.6.3. Amorphous Silicon Cell	8
I.7. Association of Photovoltaic Modules	8
I.7.1. Series Connection	9
I.7.2. Parallel Connection	9
I.7.3. Series-Parallel Connection	10
I.8. Different Photovoltaic Systems	10
I.8.1. On-Grid Photovoltaic System	10
I.8.2. Hybrid Photovoltaic System	11
I.8.3. Off-Grid Photovoltaic System	11
I.9. Photovoltaic Array	11
I.10. Protection of the PVG	13
I.11. The characteristics of a photovoltaic cell	14
I.12. Advantages and disadvantages of photovoltaic energy	15
I.12.1. Advantages of photovoltaic energy	15
I.12.2. Disadvantages of photovoltaic energy	16
I.13. MPPT Techniques	16
I.14. Conclusion	17
Chapter II. P&O and INC MPPT algorithms for PV System	
II.1. Introduction	18
II.2. PV cell equivalent circuit	18
II.3. PV cell I-V curve	19

II.4. Power Stages	20
II.4.1. DC/DC Converter	20
II.4.2. Main types of DC/DC converter	20
II.5. MPPT Control Technique	23
II.5.1 Definition	23
II.5.2 Operating Principle of MPPT	23
II.6. MPPT Control Algorithms	24
II.6.1 Perturbation and observation (P&O)	24
II.6.2 Incremental conductance (INC)	25
II.7. Simulation Results	27
II.7.1. Standard Conditions ($E=1000\text{W}/\text{m}^2$, $T=25\text{C}$)	28
II.7.2. Influence of Irradiance with Constant Temperature	29
II.8. Conclusion	32
Chapter III. Cuckoo Search and Kalman Filter MPPT algorithms for PV system	
III.1. Introduction	33
III.2. Kalman Filter Application Domain	33
III.3. Kalman Filter	34
III.4. Kalman Filter MPPT	35
III.5. Cuckoo Search Methods	37
III.6. Application Domain CS	37
III.7. Cuckoo search (CS) uses the following representations	37
III.8. Steps of the Cuckoo Search Algorithm	38
III.9. Random Exploration and step size	38
III.10. MPPT Control Algorithms	39
III.11. Simulation Results	40
III.11.1. Influence of Irradiance with Constant Temperature	40
III.12. Comparison of the different technique MPPT	43
III.13. Conclusion	47
General Conclusion	48

General Introduction

Introduction General

Solar energy technologies have witnessed rapid development worldwide, driven by their distinctive environmental and operational advantages such as safety, zero harmful emissions, and low noise levels. These features have contributed to the increased reliance on photovoltaic (PV) systems as an effective and sustainable source of renewable energy.

Despite the widespread adoption of solar energy technologies, operational challenges caused by various faults in PV systems still pose obstacles to achieving optimal efficiency. These faults lead to reduced power output, affect system reliability, and may cause safety risks such as overheating or system shutdowns. Hence, there is a pressing need for intelligent solutions to detect and analyze these faults accurately and at an early stage.

In this context, a set of traditional algorithms has emerged that contribute to improving the performance of PV systems, such as Maximum Power Point Tracking (MPPT) algorithms including Perturb and Observe (P&O) and Incremental Conductance (INC), which aim to enhance energy conversion efficiency. The Kalman Filter (KF) algorithm has also shown effectiveness in processing field data and predicting system behavior, alongside the use of Cuckoo Search (CS) as an intelligent optimization technique to find optimal solutions in fault conditions and fluctuations.

This research aims to study and analyze the performance of maximum power point tracking algorithms and improve the operation of photovoltaic systems using traditional algorithms such as Perturb and Observe (P&O) and Incremental Conductance (INC), in addition to filtering and prediction algorithms like the Kalman Filter (KF) and intelligent optimization techniques such as Cuckoo Search (CS). These algorithms were implemented and simulated using MATLAB to develop an effective system for fault detection and enhancing the response of photovoltaic systems.

Chapter I.

Introduction to Solar Photovoltaic System

I.1.Introduction

Solar energy is one of the most important sources of renewable energy because it is inexhaustible and environmentally friendly, and it has been used to provide lighting, heating, and electricity. The term "renewable energies" now encompasses various sectors whose implementation does not in any way deplete the initial resource. These renewable energy sources are mainly used to produce electricity.

Photovoltaic cells play an essential role in transforming solar energy into electricity without requiring mechanical means or chemical processes. This technology is constantly evolving, as are other components of photovoltaic systems. However, it is already a preferred option for ensuring electricity supply in many situations.

I.2. Historical Background

The development of photovoltaic systems is the result of continuous work over many years and contributions from various scientists throughout history.

1839: Edmond Becquerel discovered the photovoltaic effect, where he found that light can generate an electric current in materials.

1883: Charles Fritts invented the first solar cell using selenium, but it was highly inefficient.

1905: Albert Einstein explained the photovoltaic effect in a scientific paper, contributing to a better understanding of the phenomenon.

1940: The first efficient silicon solar cells were developed, and they were used in satellites.

1954: The first commercial silicon solar cell was developed, but it was very expensive.

1970: This period saw an increase in investment in the solar energy field, especially after the 1973 oil crisis.

2000: This decade saw a significant decrease in the cost of producing solar energy, making it more competitive with traditional energy sources.

2010: Millions of solar panels were installed around the world, and many companies began investing in solar energy projects.

2020: This decade has seen an increase in the use of solar energy in various sectors, including residential, commercial, and industrial.

Today, solar photovoltaic energy is one of the fastest-growing energy sources in the world, with ongoing research and development to improve its efficiency and reduce its cost.

I.3. Solar energy in Algeria

Algeria has paid great attention to solar energy over the past decade, specifically since the beginning of the second decade of the 21st century (around 2011), when the government began adopting policies and strategies aimed at developing renewable energy sources, with solar energy at the forefront. This is due to the country's vast potential in this field, especially in the southern regions where the sun shines for more than 3,000 hours annually. The map below illustrates the solar radiation potential in Algeria.

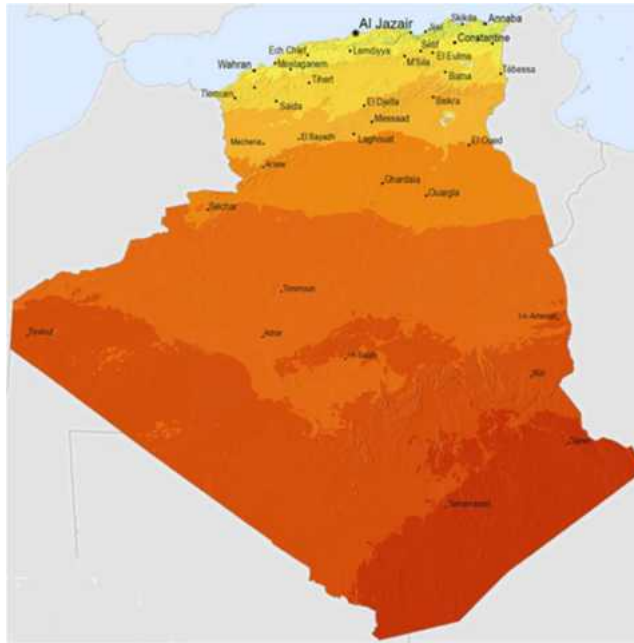


Figure (I.1). Solar radiation potential in Algeria.

I.4. Instruction of Solar Energy

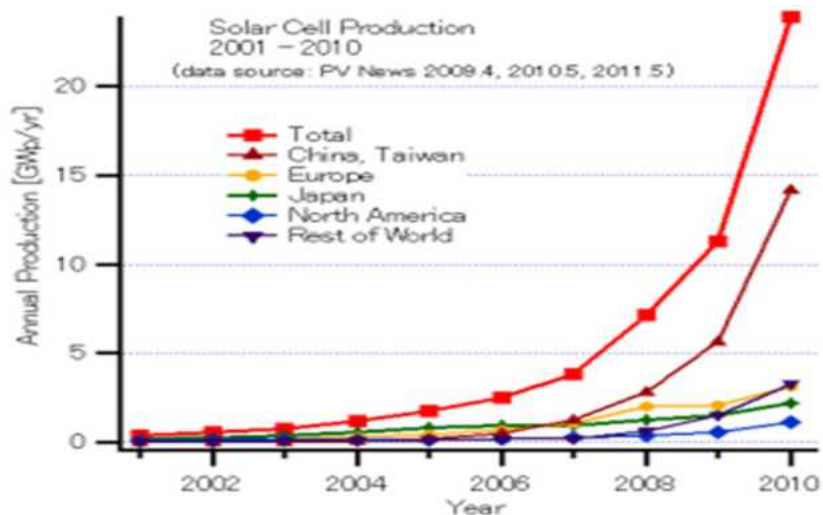


Figure 1.2 Solar cell production by region in globe.

Solar photovoltaic energy source has long been recognized as a sustainable one. By the end of 2011, a total of 67.4 GW had been installed. Following hydro and wind power, solar photovoltaic energy source is now the third most important renewable one. As shown in Figure I.2, the production of solar cell is increasing as a very high speed.

Figure I.3 shows that the solar energy potential of the world. It is clear that most of the countries can benefit from this kind of energy resources.

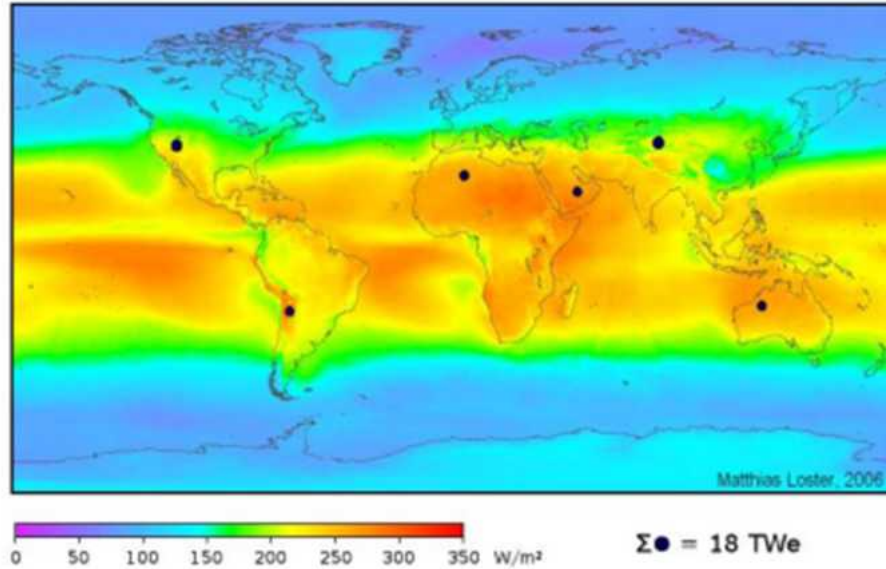


Figure I.3: Average solar irradiance.

Photovoltaic (PV) conversion is a method of generating electrical power by converting solar radiation into direct current electricity by using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material.

Photovoltaic power capacity is measured as maximum power output under standardized test conditions (STC) in "Wp" (Watts peak). The actual power output at a particular point in time may be less than or greater than this standardized, or "rated," value, depending on geographical location, time of day, weather conditions, and other factors. Solar photovoltaic array capacity factors are typically under 25%, which is lower than many other industrial sources of electricity.

I.5. Overview of Renewable Energies

Renewable energies are derived from unlimited resources and span various technological sectors, depending on the source of the exploited energy and the resulting useful energy. Several types of renewable energy sources exist, including hydroelectric energy, wind energy, biomass energy, and photovoltaic energy. These renewable energy sources originate directly or indirectly from the sun, ensuring their continuous availability as long as the sun shines.

Photovoltaic energy is the most recent addition to the array of renewable energies, providing notable advantages such as being non-polluting, flexible, and reliable. Photovoltaic systems have been in use for 40 years, initially introduced through space programs for radio transmission in satellites. Subsequently, their applications expanded to include sea beacons and the powering of isolated sites worldwide, utilizing batteries to store electrical energy during periods without sunlight, [01]. There are various types of renewable energies:

I.5.1. Hydraulic Energy

Hydraulic energy is a highly low-emission renewable energy source. This renewable energy exploits the movements of water driven by the sun and gravity through the water cycle, tides, and marine currents. (See Figure I.4).

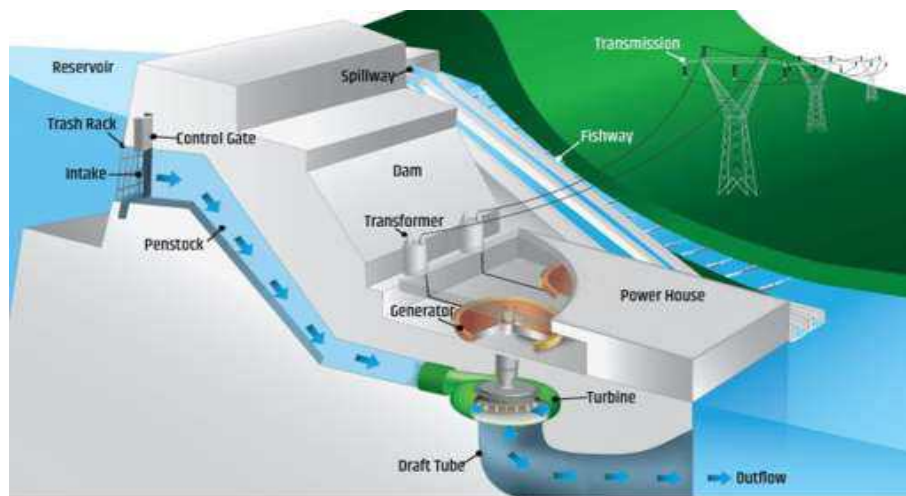


Figure (I.4). Hydraulic Power Plant

I.5.2. Geothermal Energy

Derived from the Greek terms "geo" (earth) and "thermos" (heat), geothermal energy represents both the scientific study of Earth's subsurface thermal processes and the engineering methods developed to harness this heat for practical use. As a renewable energy source, it exploits the planet's vast internal heat reservoirs—generated by ongoing radioactive decay and residual planetary formation energy—converting them into usable thermal or electrical power. This dual concept bridges fundamental geophysics with applied energy technology, enabling applications ranging from direct heating to electricity generation. The term broadly encompasses both the natural thermal phenomena occurring within Earth's crust and the engineered systems that extract this energy, as visually summarized in Figure I.5. Unlike intermittent renewables, geothermal provides stable baseload power, making it a critical component of sustainable energy portfolios worldwide.

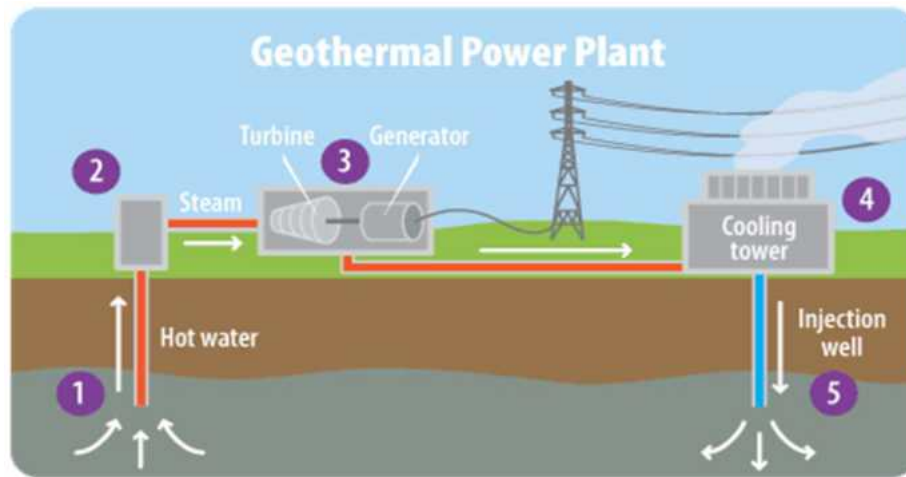


Figure (I.5). Geothermal Energy.

I.5.3. Biomass Energy

In the field of energy, specifically bioenergy, the term biomass refers to all organic matter of plant, animal, or fungal origin that can serve as a source of energy. This can be achieved through combustion (e.g., wood energy), methanization (biogas), or further chemical transformations (agrofuel). The energy derived from biomass is considered renewable and sustainable as long as there is no overexploitation of the resource. [01]

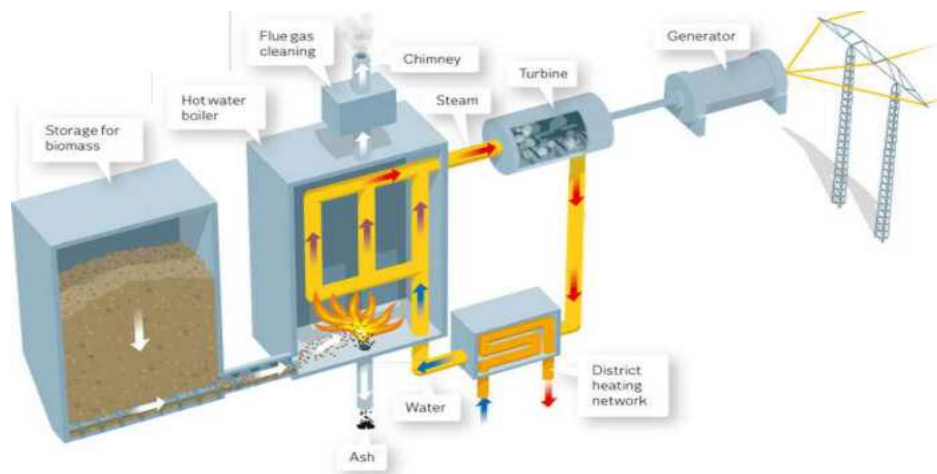


Figure (I.6). Biomass Power Plant.

I.5.4. Wind Energy

Wind energy represents a sustainable power generation method that converts atmospheric air currents into electricity. This renewable resource originates from solar-induced thermal gradients across Earth's surface, where differential heating creates regional pressure variations in the atmosphere. These pressure imbalances drive kinetic air movement—the phenomenon we recognize as wind. Modern wind power systems capture this kinetic energy through

aerodynamically optimized wind turbines, which transform the mechanical rotation of their blades into electrical power via integrated generators. As illustrated in Figure I.7 [01].



Figure (I.7). Wind Turbine.

I.5.5. Solar Energy

Solar radiation is the most uniformly distributed and abundant energy resource on Earth. The energy emitted by the sun and absorbed by the Earth in a single hour could potentially fulfill the world's energy requirements for an entire year. The sun continuously emits an enormous amount of radiant energy into the solar system, and the Earth captures only a small fraction of this solar output, (Figure I.8).

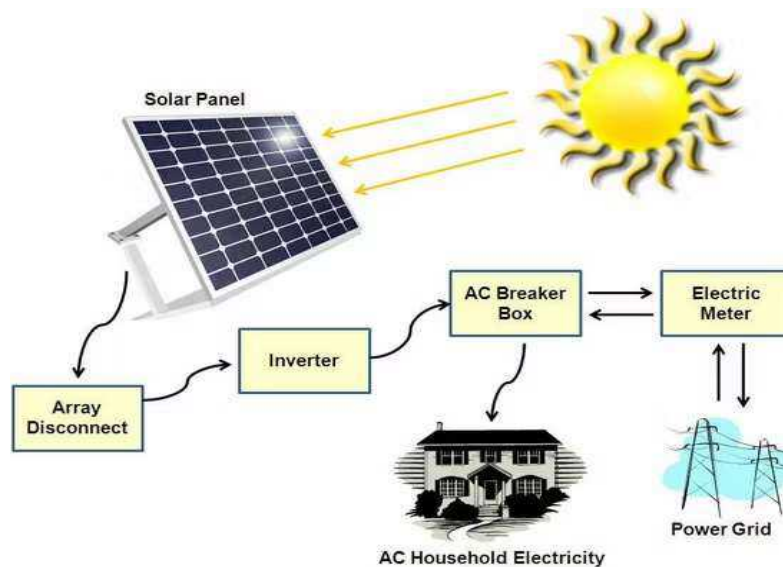


Figure (I.8). A Solar Installation.

I.6. Types of Photovoltaic Cell

There are different types of solar panels, the most commonly used are:

I.6.1. Monocrystalline Silicon Solar Cells: Monocrystalline solar cells are made from a single crystal structure, typically silicon. They offer high efficiency, ranging from 15-20%, and are known for their uniform appearance, often being colored, and have a cylindrical shape. This type of cell lasts longer, with most manufacturers providing a 25-year warranty. They perform better in low sunlight levels and are the most expensive solar cells.



Figure (I.9). Monocrystalline



Figure (I.10). Polycrystalline.



Figure (I.11). Amorphous

I.6.2. Polycrystalline Silicon Solar Cells: These solar cells are made from multiple crystals, resulting in a less uniform appearance compared to monocrystalline cells. However, they are more cost-effective, wider, and still offer good efficiency, around 13-16%.

I.6.3. Amorphous Silicon Solar Cells: Amorphous silicon solar cells have non crystalline or disordered atomic structures and can be deposited on various substrates such as glass or plastic, providing flexibility in design.

I.7. Association of Photovoltaic Modules

Modules can be connected in series and parallel to increase voltage and current intensity for practical applications. However, it is important to take precautions, as the presence of less efficient cells or the shading of one or more cells (due to shadows, dust, etc.) can permanently damage the cells.

I.7.1. Series Connection: Solar panels have positive and negative terminals. Connecting solar panels in series means connecting the positive terminal of one unit to the negative terminal of the next, and so on, along the string. This type of connection increases the output voltage, which can be measured at the available terminals.

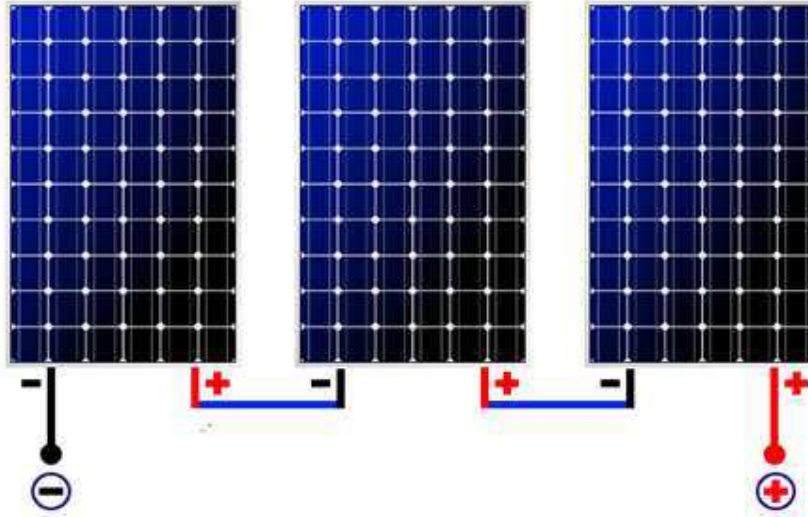


Figure (I.12). PV panels in Series.

I.7.2 Parallel Connection: Connecting solar panels in parallel increases the output current, while maintaining a constant voltage. The output current is the sum of the currents generated by the units in the string. Solar panels connected in parallel must meet NEC regulations, including conductor sizing and overcurrent devices. This is calculated by increasing the short-circuit current (I_{sc}) by 125%, taking into account the number of units in the system.

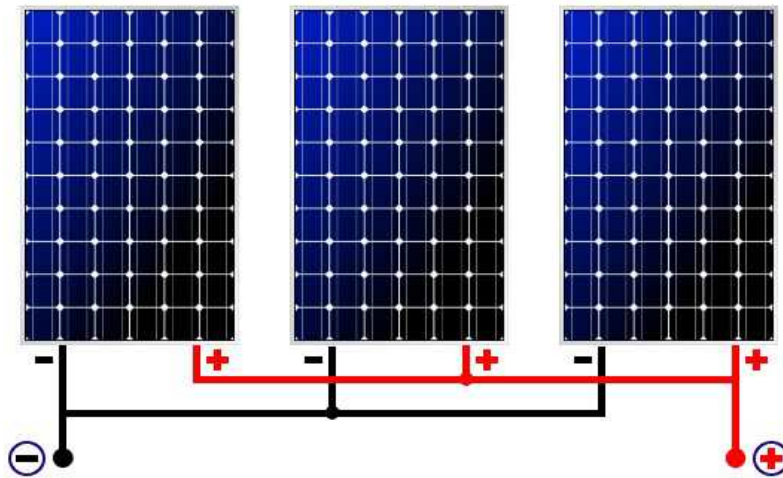


Figure (I.13). PV panels in Parallel.

I.7.3 Series-Parallel Connection: There are connections for solar panels that combine series and parallel connections, known as series-parallel connections. This connection connects solar panels in series by connecting the positive and negative terminals to increase the voltage, and then connects these strings in parallel. All solar panel strings connected in parallel must have the same voltage.

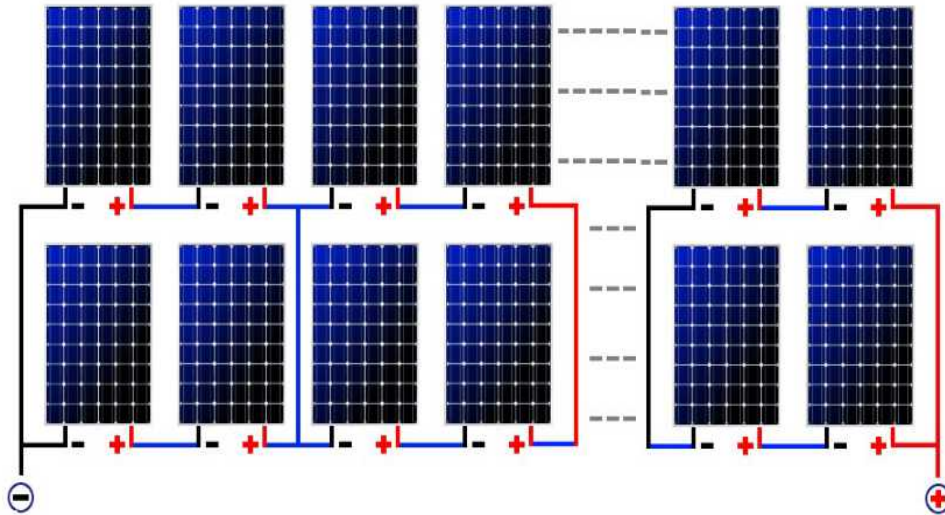


Figure (I.14). PV panels in Series-Parallel.

I.8. Different Photovoltaic Systems

There are basically three kinds of solar power systems through which electricity can be generated. These include:

I.8.1 On-grid photovoltaic system

They are solar power systems used to generate electricity from solar energy and are directly connected to the public electricity grid.

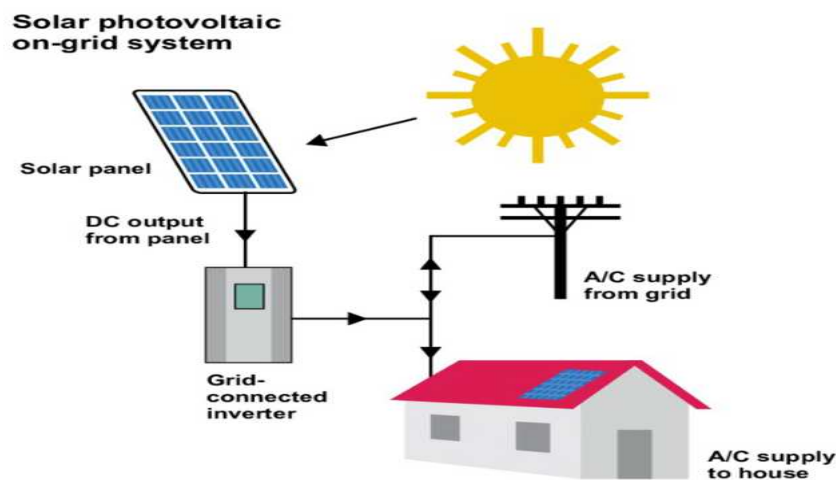


Fig (I.15.) On-Grid Photovoltaic System.

I.8.2 Hybrid Photovoltaic System

They are systems that combine the components of on-grid and off-grid systems, allowing them to operate with or without connection to the electricity grid.

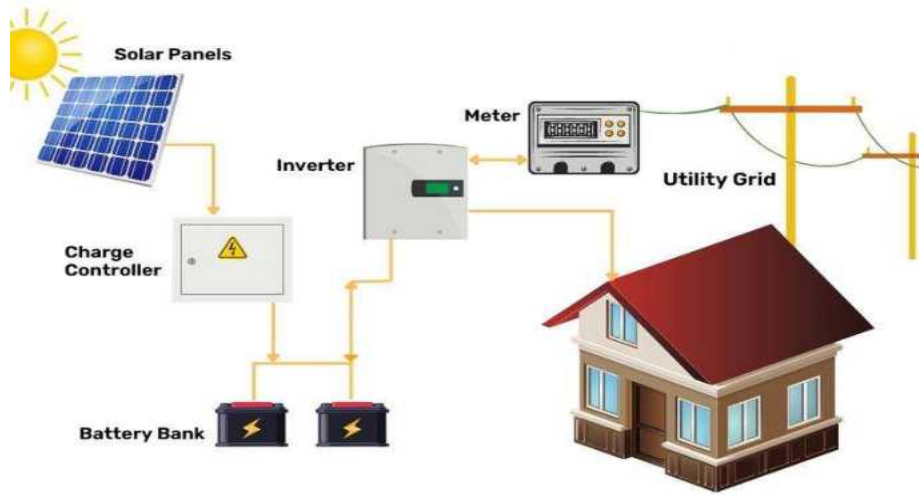


Fig I.16: Hybrid Photovoltaic System.

I.8.3 Off-grid photovoltaic system

They are solar power systems that operate completely independently from the public electricity grid and are typically used in remote areas where electrical services are not available.

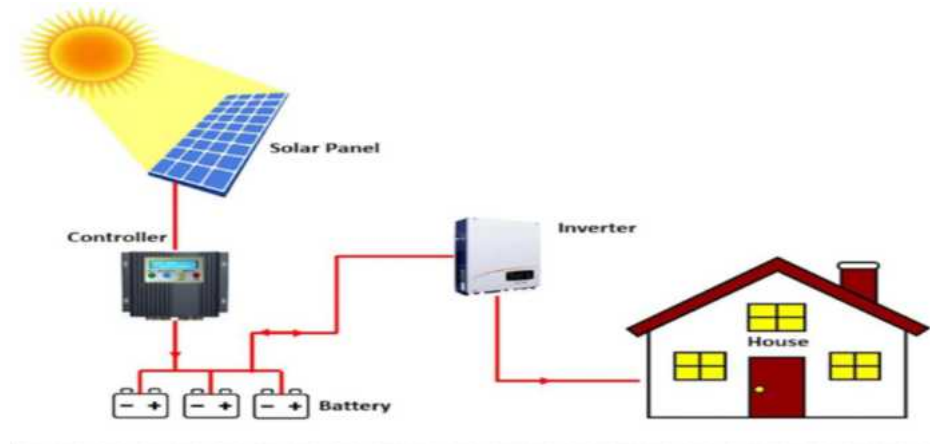


Fig I.17: Off-grid photovoltaic system.

I.9. Photovoltaic array

A photovoltaic (PV) array is a collection of solar panels interconnected to form a single unit that generates electricity from sunlight. PV arrays can be configured in series, parallel, or a combination of both to achieve the desired voltage and current output. The figure (I.18) shows the constitution of a photovoltaic array.

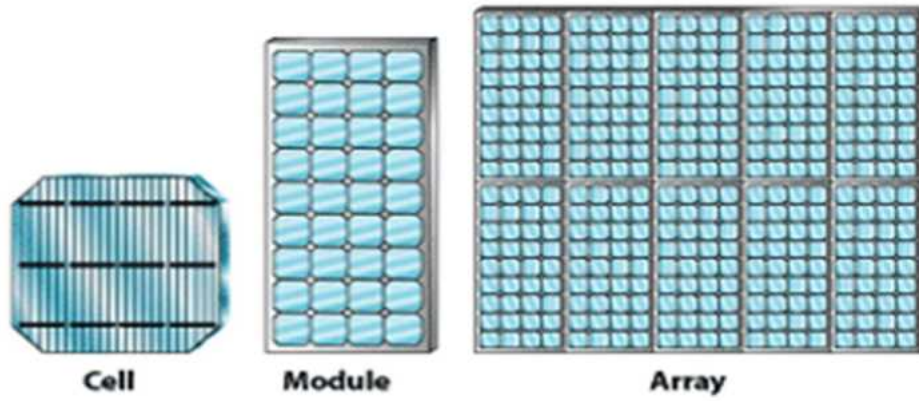


Figure (I.18). The constitution of a photovoltaic array.

An association of n_s cells in series increases the voltage, the cells will be crossed by the same current. The output voltage is the addition of every PV cell voltage as can be noticed from the next equation and figure (I.19).

$$V_{OC_{ns}} = n_s \cdot V_{OC}$$

$$I_{SC_{ns}} = I_{SC}$$

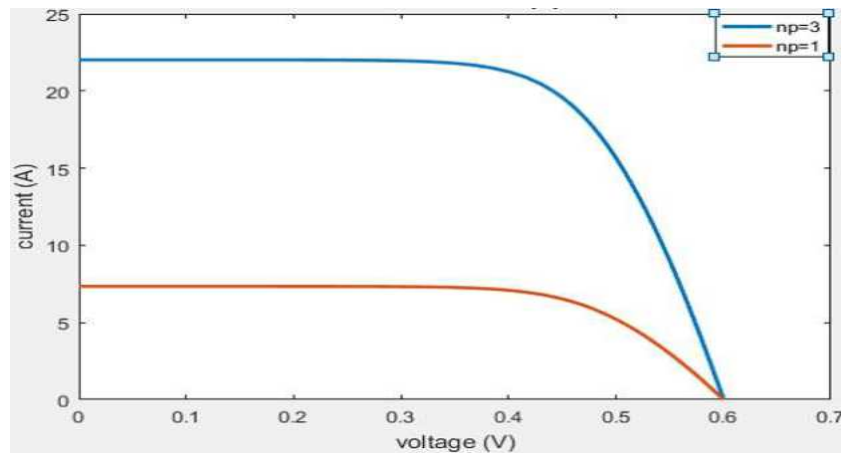


Figure (I.19). I-V characteristic for n_s PV cells.

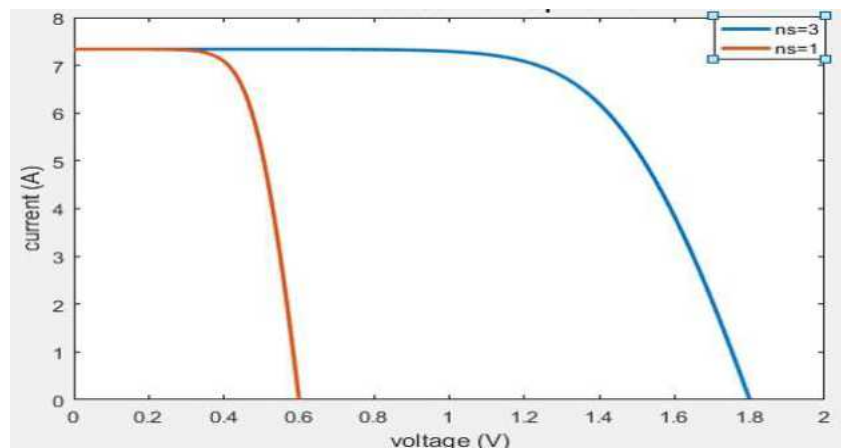


Figure (I.20). I-V characteristic for n_p PV cells.

On the other side, a parallel association of np cells increases the current provided by the generator. A number of cells connected in parallel are under the same voltage. The output current is the addition of every PV cell current as presented in the equation and the figure (I.20).

$$V_{OC_{np}} = V_{OC}$$

$$I_{SC_{np}} = n_p \cdot I_{SC}$$

The operating voltage depends on the configuration of the power supply system, and the surface area of the module is variable depending on the constructor. The assembly of the modules in series and/or in parallel will make it possible to adjust different voltages and powers.

I.10. Protection of the PVG

To guarantee uninterrupted power supply under diverse conditions and prevent solar cell degradation, two fundamental protection methods are employed:

❖ Series Connection Protection

In series-connected solar cells, the current remains constant throughout the circuit while the voltages accumulate. If a cell is subjected to uneven irradiance relative to other cells, it can become a vulnerability point, receiving reverse voltage from other cells and potentially absorbing excessive energy, which may lead to damage if the voltage surpasses a certain threshold. To mitigate this risk, bypass diodes are utilized, connected in parallel with the cells. These diodes enable current to circumvent the affected cell, thereby preventing damage. Due to economic considerations, diodes are not typically installed for each individual cell. Instead, two diodes are often used to protect each module comprising 36 cells, effectively minimizing the risk of -hot spot- damage while maintaining adequate protection.

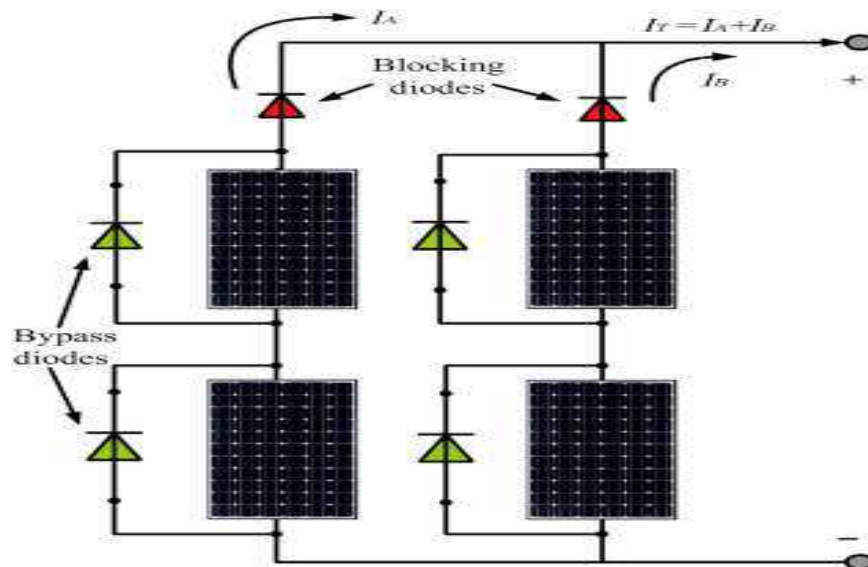


Figure (I.21). Bypass diode and blocking diode.

❖ Parallel Connection Protection

In parallel connections, solar cells maintain a constant voltage while their currents aggregate. However, if a single cell experiences a fault or shading, it can lead to excessive current flow from other cells into the affected cell, potentially causing overheating or damage. To mitigate this risk, blocking diodes are employed, typically installed on each parallel string of cells. These diodes effectively block reverse current flow between strings, safeguarding the system against damage resulting from uneven solar irradiance or cell failures.

I.11. The characteristics of a photovoltaic cell

Photovoltaic cells (PV cells) possess several important characteristics that determine their performance and efficiency. Here characteristics:

- **Efficiency:** Efficiency is the ratio of electrical energy output to the solar energy input. Efficiency depends on the quality of materials used and cell design.
- **Voltage and Current:** Voltage and current are the two main parameters of a PV cell. Voltage is the difference in electrical potential between the cell terminals, and current is the flow of electrons through the cell.
- **Power:** Power is the product of voltage and current, representing the electrical energy output of the cell.
- **Temperature:** Temperature affects the performance of a PV cell. Increased temperature can reduce cell efficiency.
- **Angle of Incidence:** Angle of incidence is the angle between the incident light and the cell. Angle of incidence affects the amount of light reaching the cell.
- **Internal Resistance:** Internal resistance of a PV cell affects its efficiency. Lower internal resistance means higher efficiency.
- **Shading Effect:** Shading effect can reduce the performance of a PV cell. Shading can cause a decrease in current and voltage output of the cell.

Taking for example a cell from the Sun Power SPR-76R-BLK-U module, this module has the following characteristics at 1000 (W/m²) and 25°C:

Table (I.1). Characteristics of the Sun Power SPR-76R-BLK-U module.

P (W)	V _{oc} (V)	I _{cc} (A)	V _{mp} (V)	I _{mp} (A)
235	36.96	8.48	29.42	7.99

The following figures represent the characteristics of the PV panel in operation for different temperatures and solar irradiations.

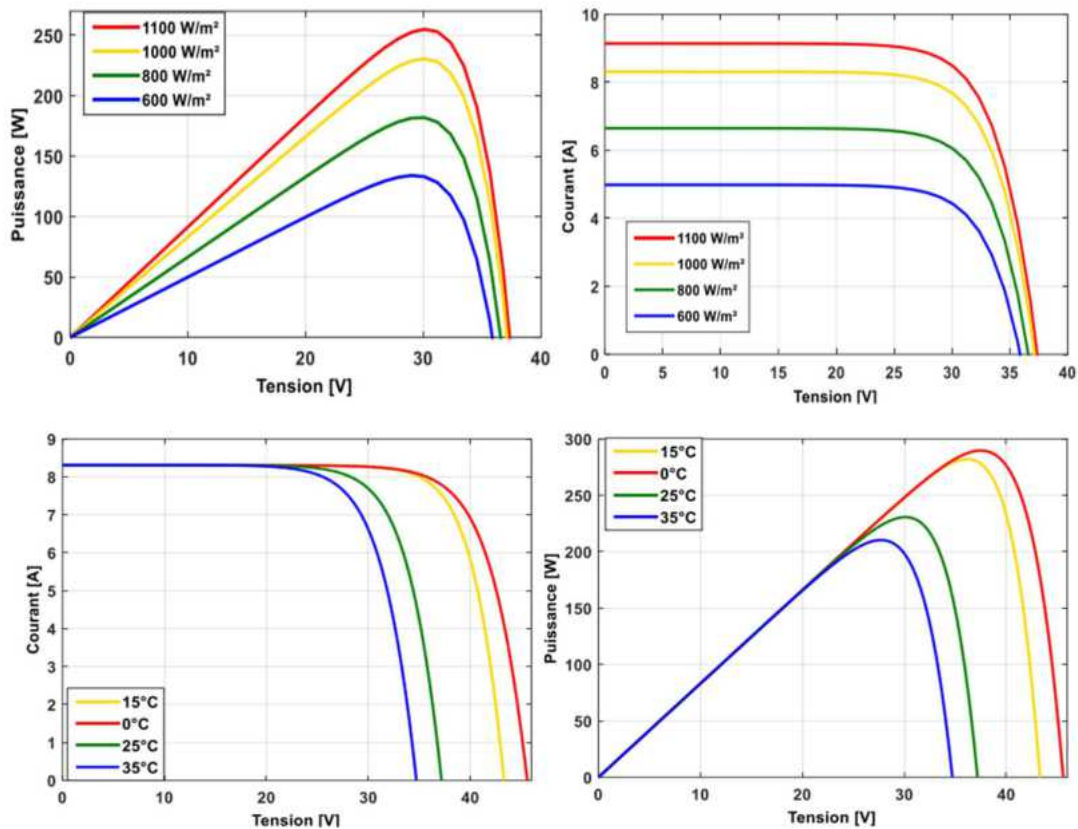


Figure (I.22). Characteristics of a PV for different temperatures and irradiances conditions.

I.12. Advantages and disadvantages of photovoltaic energy

I.12.1 Advantages of Photovoltaic Energy

Photovoltaic energy has several advantages that make it an attractive option for generating electricity. Here are some key benefits.

- ❖ **Renewable Energy Source:** Photovoltaic energy relies on the sun as a source of energy, making it a renewable and inexhaustible resource.
- ❖ **Environmentally Friendly:** Photovoltaic energy does not produce any harmful emissions of greenhouse gases, making it an environmentally friendly option.
- ❖ **Low Operating Costs:** After installation, the operating and maintenance costs are very low.
- ❖ **Independence from the Electrical Grid:** Photovoltaic energy can be used in remote areas or places where there is no electrical grid.
- ❖ **Diverse Applications:** Photovoltaic energy can be used in a wide range of applications, from residential homes to large industrial projects.

I.12.2 Disadvantages of photovoltaic energy

Despite the many advantages of photovoltaic energy, there are some disadvantages that need to be considered.

- Weather Dependence: Photovoltaic energy production is affected by weather conditions, where clouds and shading can reduce production.
- High Initial Cost: Despite the decrease in cost in recent years, the initial cost of photovoltaic cells is still high.
- Land Area: Photovoltaic power plants require large areas of land, which can lead to conflicts over land use.
- Energy Storage: There is no effective solution for storing solar energy, which means that the energy produced must be used in real-time or stored using expensive batteries.
- Shading Effect: Shading can affect the performance of photovoltaic cells, reducing their efficiency.

I.13. MPPT Techniques

The main challenge in solar power systems is the variable and dynamic nature of the energy source, where voltage and power levels are affected by several environmental factors such as solar radiation intensity and temperature. To ensure the operation of photovoltaic (PV) panels at the highest possible efficiency, Maximum Power Point Tracking (MPPT) techniques are applied. These techniques are among the most important areas of research currently, especially in the fields of predicting solar productivity and analyzing the relationship between voltage and current to reach the maximum power that can be obtained from the solar system.

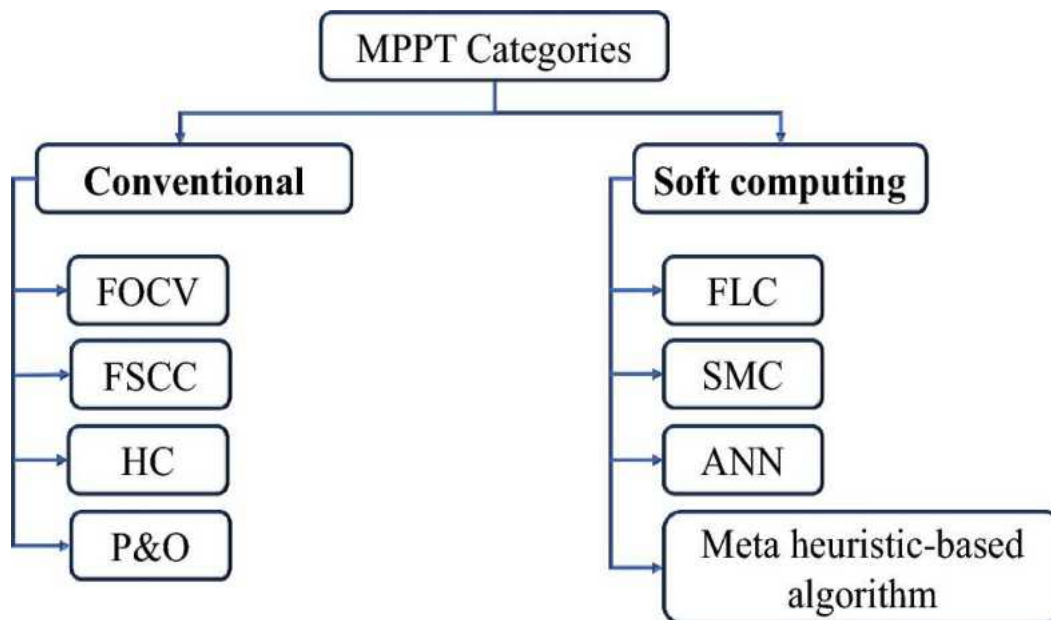


Figure (I.23). Common types of MPPT methods for PV systems

I.14. Conclusion

Solar photovoltaic systems play a crucial role in the transition to renewable and sustainable energy globally. With their ability to provide clean energy at competitive prices, these systems are poised to make a significant impact in the future.

Chapter II.

P&O and INC MPPT algorithms for PV system

II.1. Introduction

Photovoltaic (PV) systems are a vital source of renewable energy, but their efficiency heavily depends on maximizing power extraction under varying environmental conditions such as solar irradiance and temperature. Maximum Power Point Tracking (MPPT) algorithms are essential for optimizing the power output of PV systems by continuously adjusting the operating point to the maximum power point (MPP). Among various MPPT techniques, the **Perturb and Observe (P&O)** and **Incremental Conductance (INC)** algorithms are widely used due to their effectiveness and relative simplicity.

This chapter focuses on the modeling and simulation of a solar power system integrated with different Maximum Power Point Tracking (MPPT) techniques, specifically the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms. The performance of these MPPT methods will be assessed in terms of efficiency, dynamic response, and load adaptability.

The mathematical model of the photovoltaic (PV) system is developed based on the fundamental equations governing the PV equivalent circuit. To validate the design, simulations are conducted using MATLAB/Simulink, providing a comprehensive analysis of system behavior under varying operational conditions.

II.2. PV cell equivalent circuit

An ideal PV cell can be presented by a current source with a diode connected in parallel. In the ideal case, the series and shunt resistances are considered to be zero and infinite, respectively. However, in real system, both the series and shunt resistances have finite values and must be considered. In Fig.II.1(a & b), both the ideal and practical equivalent circuits of a solar cell are shown. The generated current (I) by the PV cell is given by:

$$I = I_{ph} - I_{sh} - I_D$$

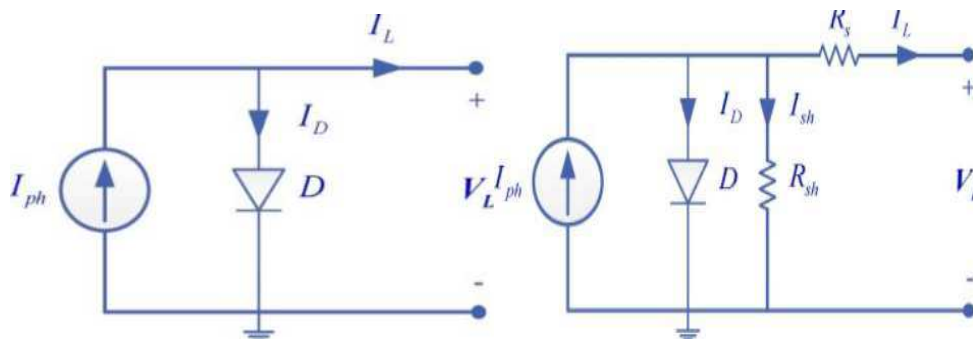


Figure (II. 1): Equivalent circuit of Solar cell ideal (a) and (b) practical.

$$I = I_{ph} - \left(\frac{V + I \cdot R_s}{R_{sh}} \right) - I_o \left(e^{\frac{v + I \cdot R_s}{nV_T}} - 1 \right)$$

Where V_T is the thermal voltage, R_s and R_{sh} represent the internal series and parallel resistances respectively. I_{ph} is the short-circuit current, I_o is the reverse saturation current, I is the current output and n is the ideality factor of the diode.

A simplified model after neglecting the shunt resistance is shown in Fig. 1a, and accordingly the following equation can be derived.

$$I = I_{ph} - I_o \left(e^{\frac{v + I_{ph} \cdot R_s}{nV_T}} - 1 \right)$$

PV cell output voltage can be found with $T = KT/q$.

$$V = -I_{ph} \cdot R_s + \frac{A \cdot K \cdot T}{q} \ln \left(\frac{I_{ph} + I_o - I_{ph}}{I_o} \right)$$

II.3. PV cell I-V curve

PV cells have a nonlinear (I-V) characteristic, which changes the (I-V) curve of a PV cell as shown in Fig (II.2), where the temperature is 25°C and the irradiation level is 1000 W/m². The maximum power point is always at the knee of the curve, and it varies with irradiation level and temperature, as indicated for standard conditions.

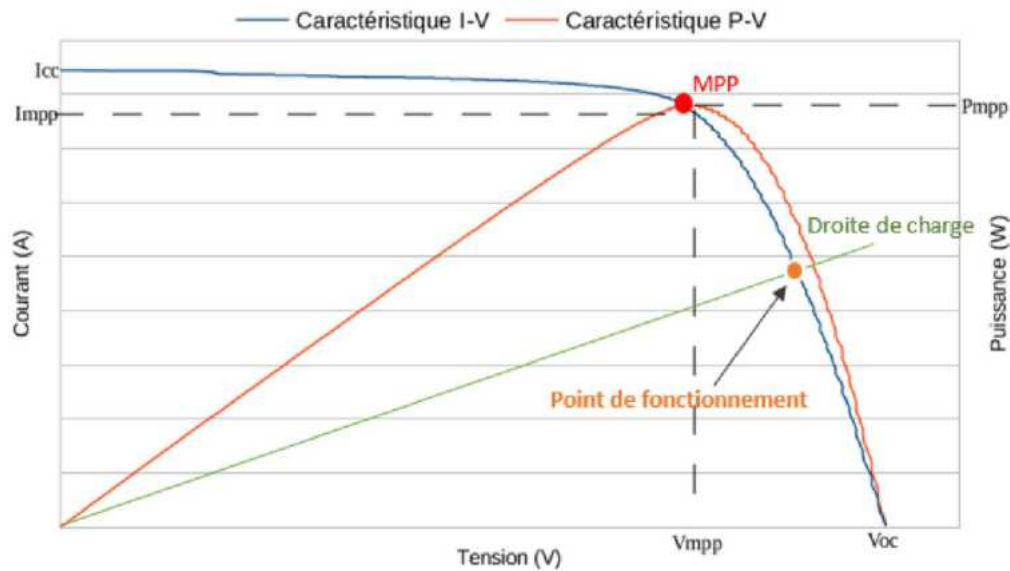


Figure (II. 2): General (I-V) curve of PV cell

II.4. Power Stages

To ensure optimal power transfer between the PV array and the load, a power conditioning stage is required. This typically involves a **DC-DC converter**, which regulates voltage and current levels to maximize efficiency. The following section presents an analysis of different **DC-DC converter topologies** and their suitability for photovoltaic applications.

II.4.1. DC/DC Converter

A DC/DC converter is an essential power electronic device that regulates and converts direct current (DC) voltage from one level to another. These converters play a critical role in various applications, including electronic devices, power distribution systems, electric vehicles, and renewable energy systems such as photovoltaic (PV) installations.

In solar energy systems, DC/DC converters serve as a key interface between the PV array and the load, ensuring efficient power transfer and maximum energy extraction. The typical configuration, illustrated in Figure II.3.

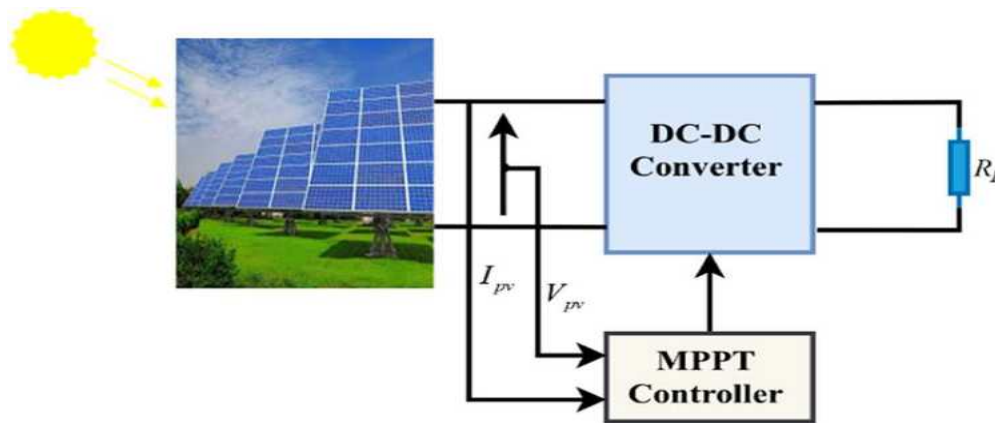


Figure (II.3): PV -load connection via power stage.

II.4.2 Main types of DC/DC converters

A. Buck Converters.

It is used to reduce the input voltage to a lower output voltage level while maintaining the same type of current (direct current). In terms of operation, the buck converter works by rapidly switching an electronic switch (such as a transistor) on and off. It uses an inductor and a capacitor to smooth and convert the output voltage. When the switch is on, the inductor stores energy, and when the switch is off, the inductor releases the stored energy to the load.

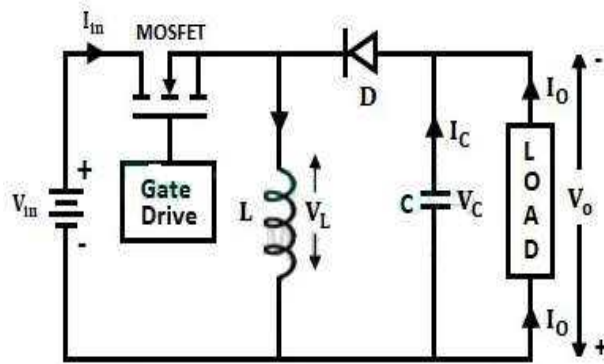


Figure (II.4): Buck converter.

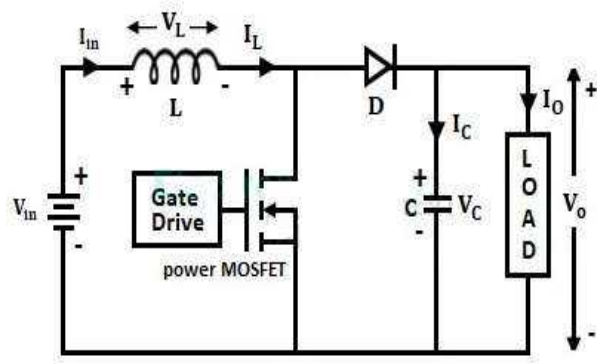


Figure (II.5): Boost converter.

B. Boost Converter

The boost converter is a power converter with a dc output voltage higher than its dc input voltage. It contains two semiconductors (diode, switch) and at least one energy storage element. The output capacitor is added to reduce output voltage ripple. Also, the boost converter is called a step-up converter. The figure (II.5) indicates the circuit of the boost converter.

The figure (II.6) shows the switch's state:

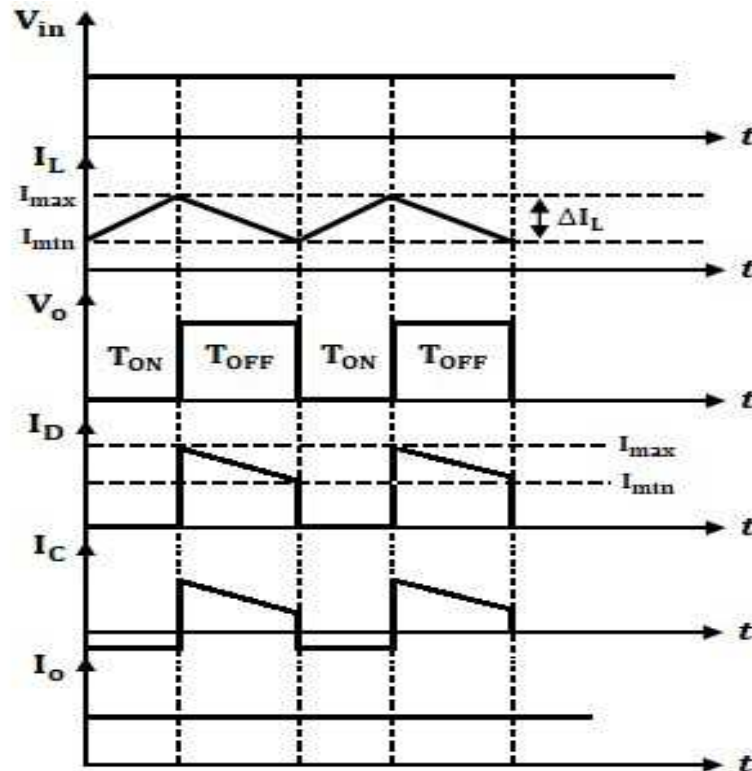


Figure (II.6): Waveform of a DC-DC boost converter.

We define the duty cycle as: $D = \frac{T_{on}}{T}$

$[0, T_{on}]$: The switch (S) is closed, the inductance current increasing progressively, the inductance stores up energy. The figure (II.7) presents the boost converter in the on time.

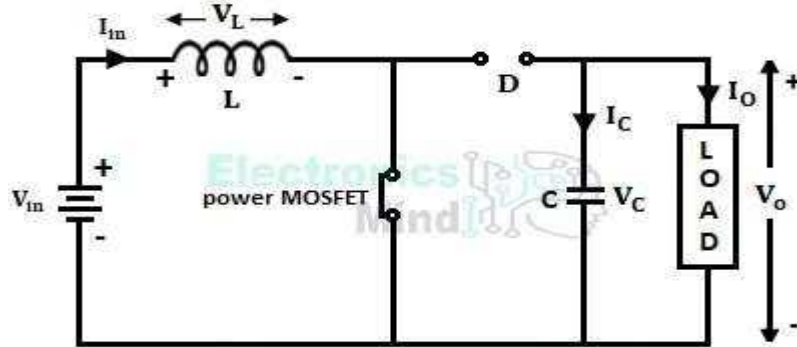


Figure (II.7): Boost converter during on time.

The voltage across the inductor is:

$$V_i = N_L$$

The mathematical equation characterizing the inductance current is given by:

$$\frac{dI_L}{dt} = \frac{V_i}{L}$$

$[T_{on}, T]$: The switch (S) is open, the inductance generates a voltage which is added to the source voltage, which is applied to the load (R) through the diode (D). The figure (II.8) presents the boost Converter during off time.

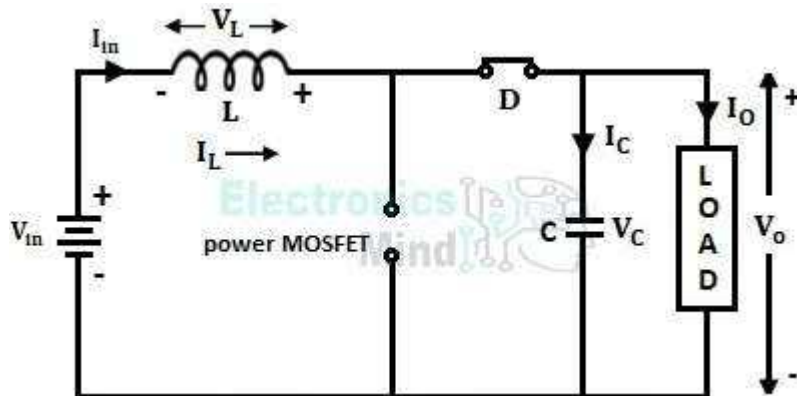


Figure (II.8): Boost converter during Off time.

The voltage across the inductance is:

$$V_L = V_i + V_S$$

The mathematical equation characterizing the inductance current is given by:

$$\frac{dI_L}{dt} = \frac{V_i - V_S}{L}$$

The average value of the voltage V_L is zero:

$$\langle V_L \rangle = \int_0^T V_L dt = 0$$

So:

$$\langle V_L \rangle = (V_i)(D * T - 0) + (V_i - V_s)(T - D * T) = 0$$

Then,

$$V_s = \frac{V_i}{1-D}$$

With:

$$I_0 = I_i(1-D)$$

The design of the boost converter inductance depends essentially in the current ripple which is inversely proportional to the inductance value as shown in the next equation.

$$L = \frac{V_i * D}{\Delta I * f_{sw}}$$

On the other side, some types of loads require an alternative voltage source, but the PV panel generates direct current, so, the direct connection is not possible in this case.

II.5. MPPT Control Technique

II.5.1 Definition

Maximum Power Point Tracking (MPPT) is an essential control technique employed in photovoltaic systems to continuously optimize power output from solar panels. By dynamically adjusting the electrical operating point, MPPT algorithms ensure the photovoltaic array operates at its maximum power point (MPP) despite variations in environmental conditions such as solar irradiance and temperature.

This advanced regulation method significantly improves system efficiency by typically increasing energy harvest by 20-30% compared to non-MPPT systems. MPPT controllers achieve this optimization by automatically varying the duty cycle of connected DC-DC converters, thereby adjusting the impedance matching between the solar panels and the load.

II.5.2 Operating Principle of MPPT

Maximum Power Point Tracking (MPPT) is an adaptive control technique that dynamically adjusts the electrical operating point of a photovoltaic (PV) system to maintain optimal power extraction. The fundamental operating principle involves continuously monitoring the PV array's

current-voltage (I-V) characteristics and automatically regulating the system impedance to operate at the maximum power point (MPP), where the product of voltage and current reaches its peak value.

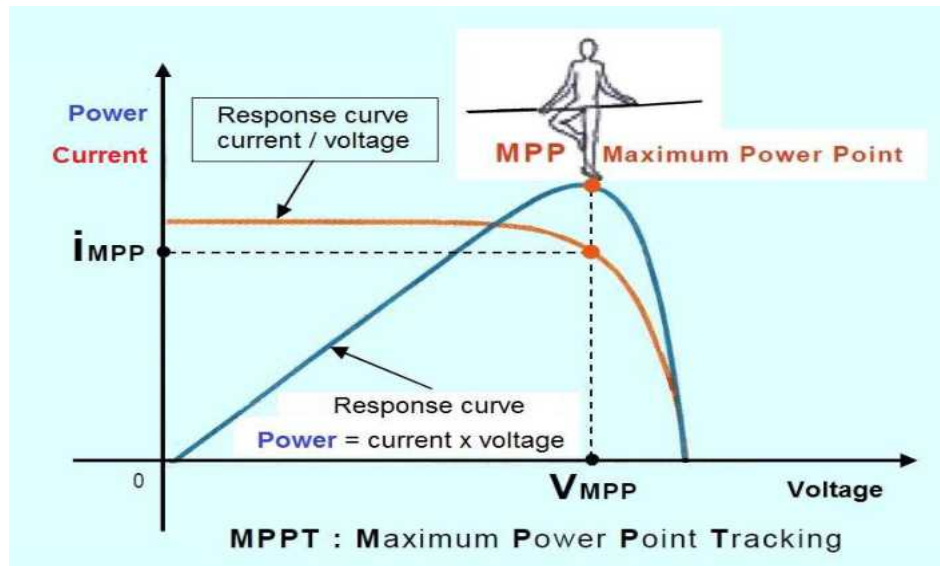


Figure (II.9): Principle of MPPT control.

II.6. MPPT Control Algorithms

The performance of photovoltaic panels is significantly affected by climatic variables, such as solar irradiance intensity, temperature, air mass spectrum, and shading phenomena. To achieve maximum electrical energy production, buck converters are typically used within the conversion system. In this context, various control algorithms have been developed to track the Maximum Power Point (MPPT). Hill-climbing techniques are among the most common methods, relying on tracking the power-voltage curve to extract the maximum possible energy. Two prominent techniques are the Perturb and Observe (P&O) algorithm and Incremental Conductance (INC) algorithm, both widely used due to their simplicity and effectiveness under varying operating conditions.

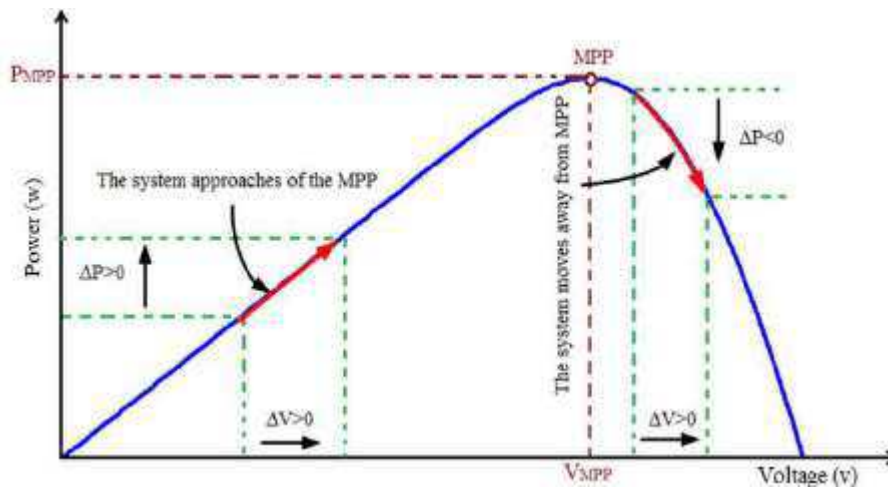
II.6.1 Perturbation and observation (P&O)

The P&O method is the most popular MPPT algorithm due to its simplicity. It's one of the Hill climbing algorithms. The objective of this algorithm is to operate the system at its maximum power by incrementing or decrementing the voltage at the operating point and observing the effect of this perturbation on the power (figure II.10). The table (II.1) shows the response of the control system for each case [23]:

Table (II.1): The response of the control system for each case of P&O algorithm.

Case n°	ΔV	ΔP	$\frac{\Delta P}{\Delta V}$	Direction of tracking	Reponses of the control
1	+	+	+	Good	Incrementing: $V_{ref} = V_{ref} + V$
2	-	-	+	Bad	Incrementing: $V_{ref} = V_{ref} + V$
3	+	-	-	Bad	Decrementing: $V_{ref} = V_{ref} - V$
4	-	+	-	Good	Decrementing: $V_{ref} = V_{ref} - V$

Different cases are shown in the figure (II.9):

**Figure (II.10):** Different possible cases for the functioning of P&O Algorithm

II.6.2 Incremental conductance (INC)

In the incremental conductance method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change. This method requires more computation in its controller, but can track changing conditions more rapidly than the perturb and observe method. With this method,

if $\frac{\partial I_{pv}}{\partial V_{pv}} > -\frac{I_{pv}}{V_{pv}}$, the slope of P-V curve is positive;

if $\frac{\partial I_{pv}}{\partial V_{pv}} < -\frac{I_{pv}}{V_{pv}}$, then it will be negative.

Unless $\frac{\partial I_{pv}}{\partial V_{pv}} = -\frac{I_{pv}}{V_{pv}}$, which means the operating point matches the maximum power point.

For discrete system, $\partial I_{pv}(k) = I_{pv}(k) - I_{pv}(k-1)$, $\partial V(k) = V_{pv}(k) - V_{pv}(k-1)$

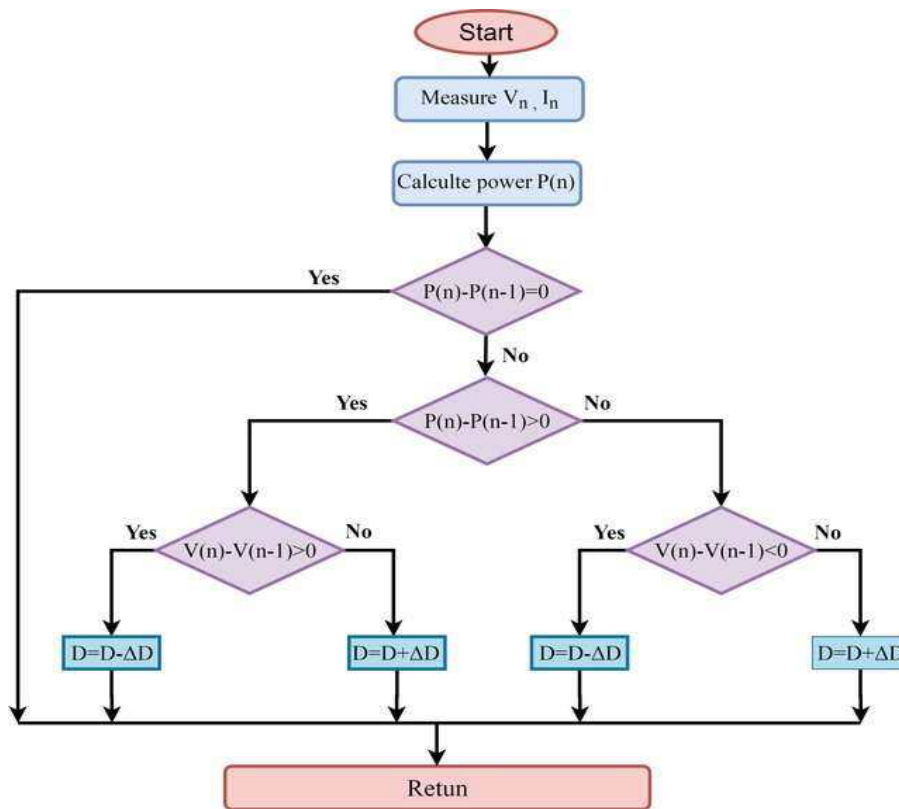


Figure (II.11): Flowchart of P&O MPPT method.

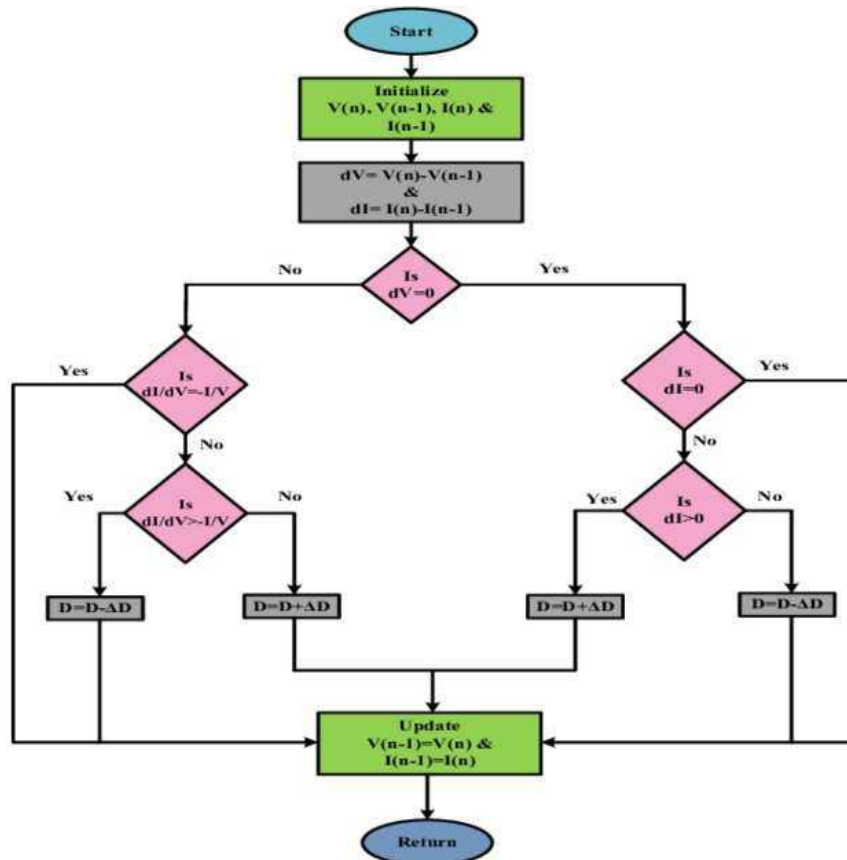


Figure (II.12): Flowchart of INC MPPT method

II.7. Simulation Results

In this work, the photovoltaic PV array a 960.69 W was constructed using four solar panels connected in series ($4n_s$) and one parallel string ($1n_p$). The PV array model was based on the **schuco USA MPE180MS05** model from the *Matlab/Simulink* library. Table (II.2) presents the key characteristics of both the single solar panel and array PV model.

Table (II.2): PV model characteristics.

	PV	PV Array
Maximum power (P_{mpp})	240.1725W	960.69 W
Maximum current (I_{mpp})	7.75 A	7.75 A
Maximum voltage (V_{mpp})	30.99 V	123.96 V
Open circuit voltage (V_{oc})	38.92 V	155.68 V
Short circuit current (I_{cc})	8.2 A	8.2 A

The figure (II.13) presents the current-voltage (I-V) and power-voltage (P-V) curves obtained from the PV panel Simulink model under various irradiance conditions. These curves illustrate the impact of changing environmental factors on the electrical behavior of the PV array. By analyzing the I-V and P-V curves, we can gain valuable insights into parameters like the maximum power point (MPP) voltage (V_{mpp}) and current (I_{mpp}), which are crucial for optimizing the PV system's performance.

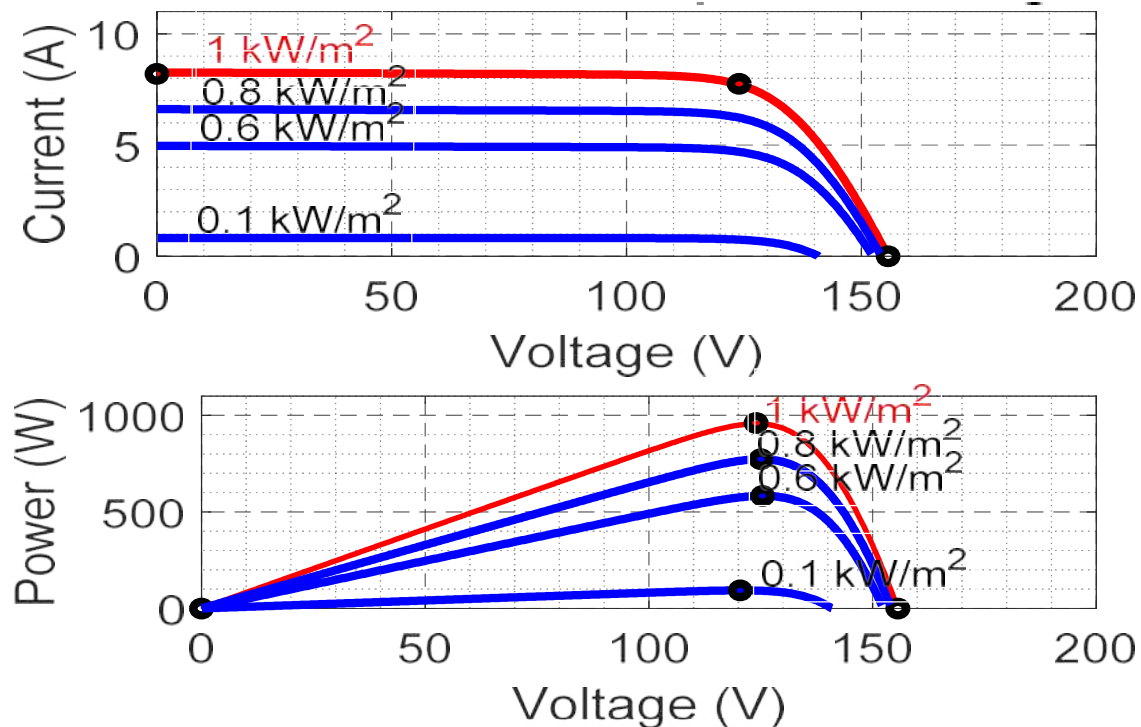
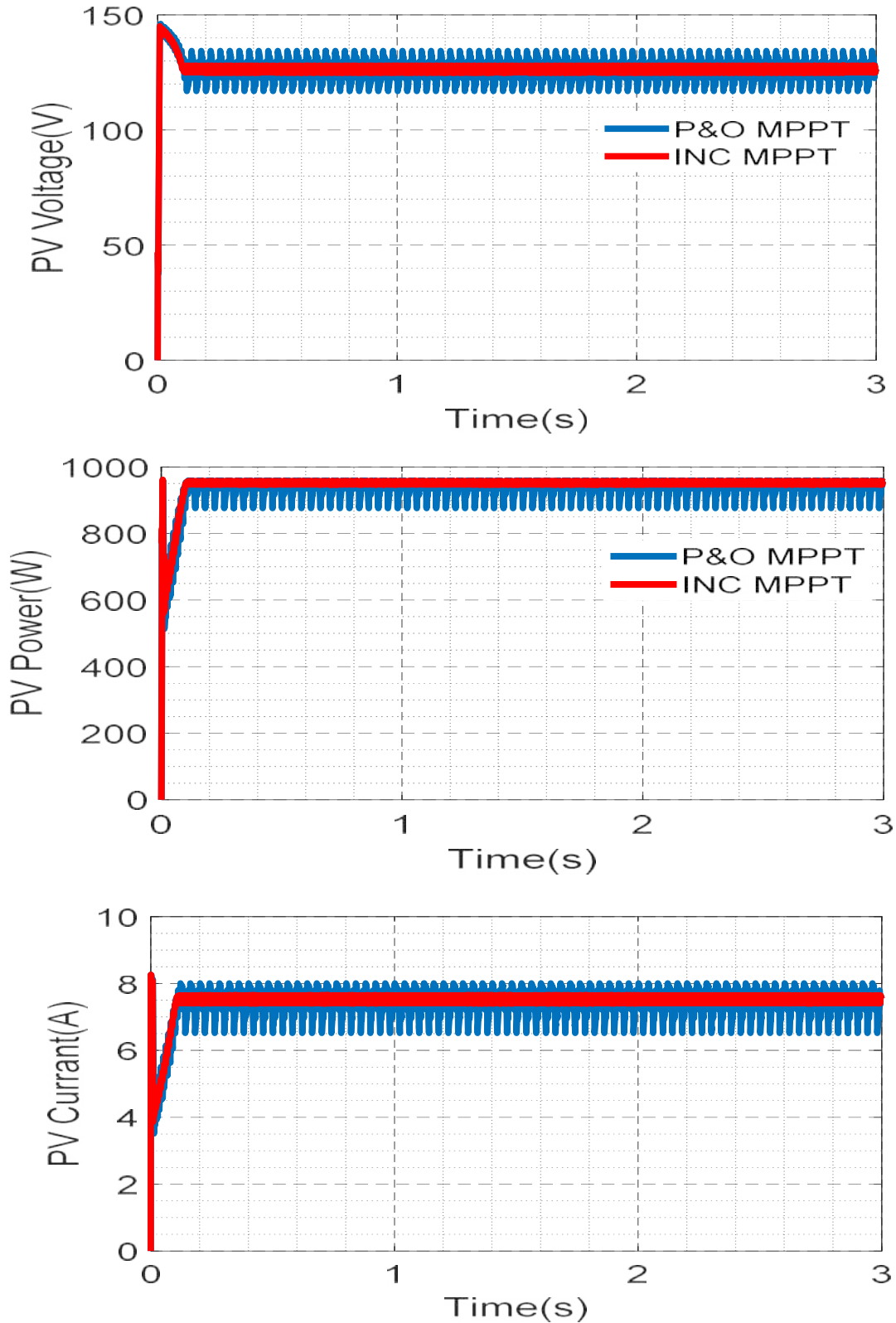


Figure (II.13): I-V and P-V curves for PV array under various irradiance conditions

II.7.1. Standard Conditions ($E=1000\text{W/m}^2$, $T=25\text{C}$)

❖ P&O and INC Algorithm

Figure (II.14): Simulation results of the PV at ($T=25\text{C}$, $E=1000\text{W/m}^2$)

📊 Interpretation of the Results:

Under standard test conditions (STC), which include a solar irradiance of 1000 W/m^2 and a temperature of 25°C , the simulation results showed that Maximum Power Point Tracking (MPPT) techniques using both Perturb and Observe (P&O) and Incremental Conductance (INC) were effective. This was evident through the increase in output power until the Maximum Power Point (MPP) was reached, after which the power stabilized during the simulation period.

The results also demonstrated the efficiency of the converter in boosting the voltage, as the output voltage was consistently higher than that directly provided by the photovoltaic (PV) module. It is worth noting that the INC method exhibited a faster response in reaching the MPP with less power fluctuation compared to the P&O method.

II.7.2. Influence of Irradiance with Constant Temperature

The following figures represent the results of the PV panel for the contrast in the case of variable irradiance and constant temperature ($T = 25^\circ\text{C}$):

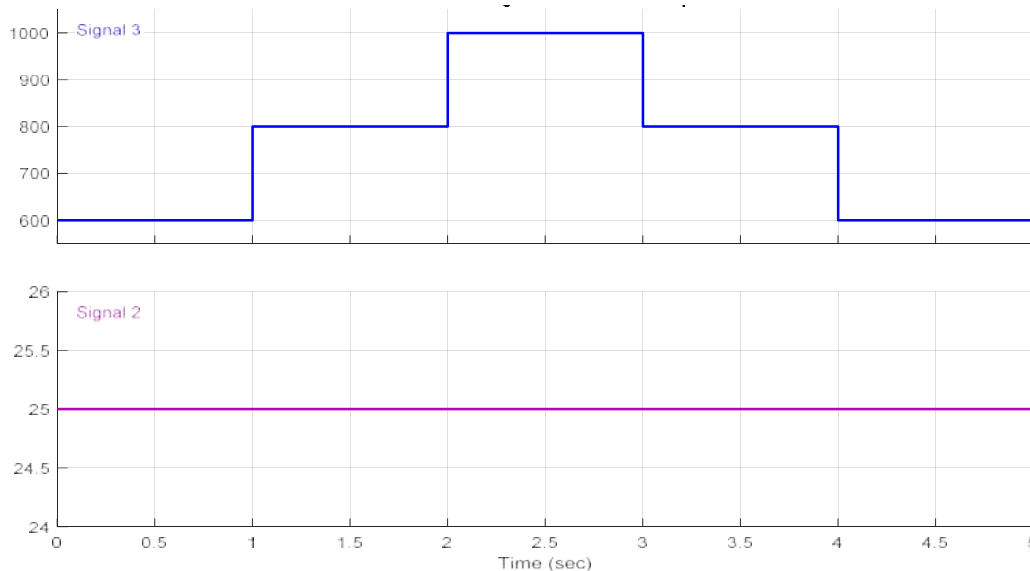


Figure (II.15): Signal builder for variable irradiance and constant temperature.

This section investigates the impact of varying irradiance levels on the performance of the PV panel while maintaining a constant temperature of 25°C (Fig.II.15). The figure (II.16) and figure (II.17) illustrate the simulation results obtained for both P&O and INC MPPT methods.

A. P&O and INC Algorithm input

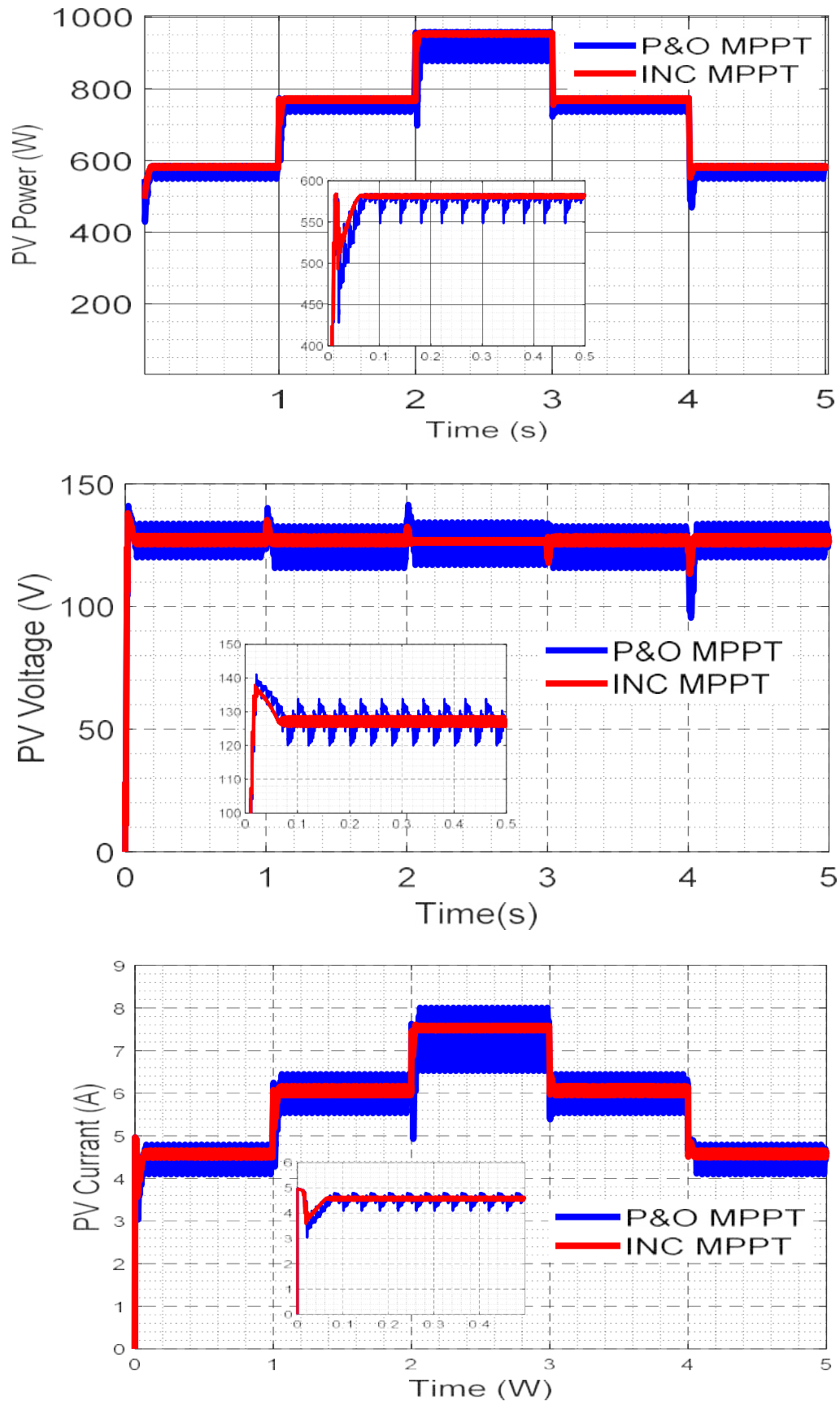
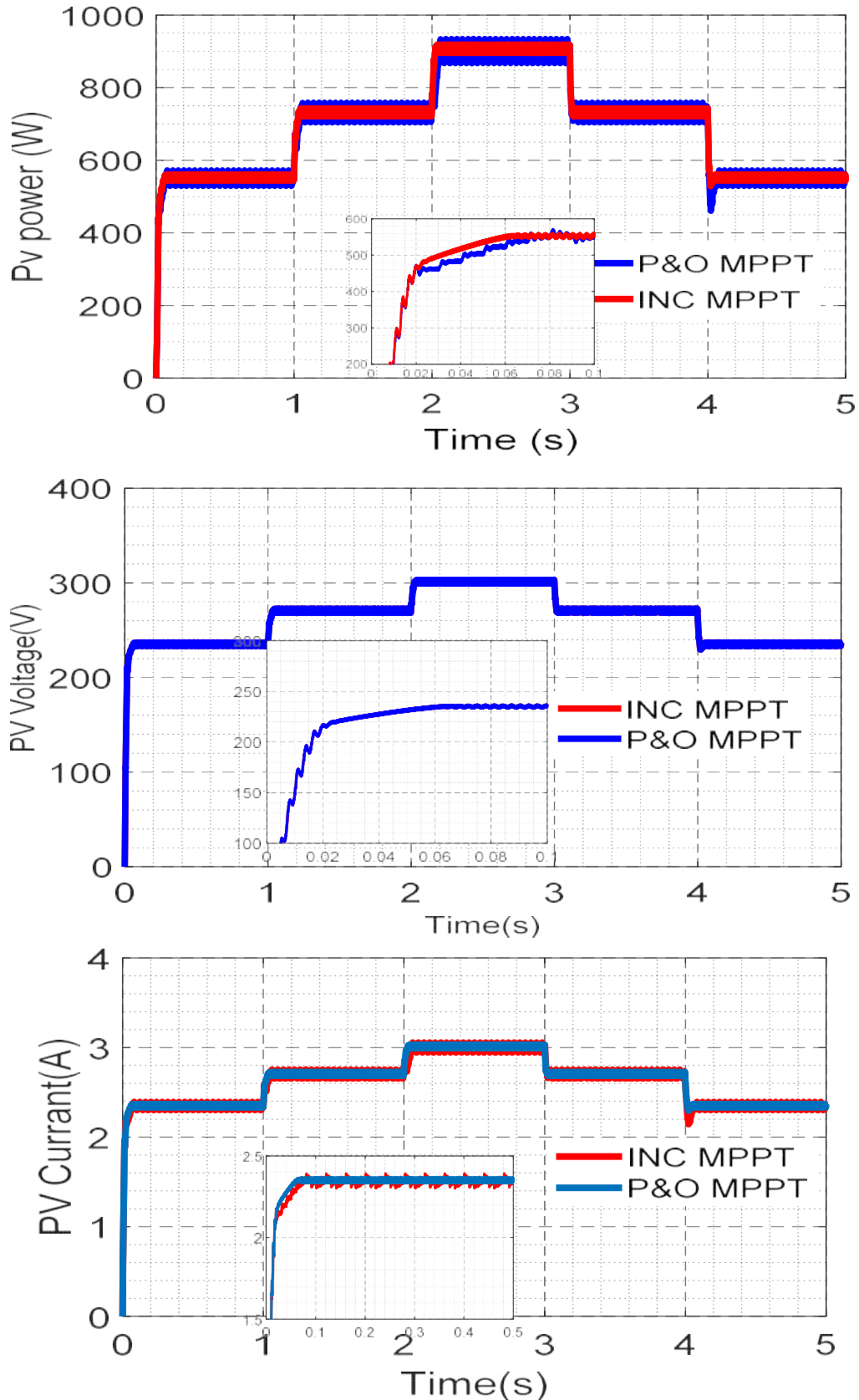


Figure (II.16): Simulation Results of the PV for Variable Irradiance and ($T=25^{\circ}\text{C}$).

B. P&O and INC Algorithm output

Figure (II.17): Simulation Results of the PV for variable irradiance and ($T=25^{\circ}\text{C}$).

A. Interpretation of the results (Input):

It is clear that both algorithms effectively track changes in power in response to variations in solar irradiance. The INC algorithm shows more stability and smoothness, while the P&O algorithm exhibits some oscillations around the maximum power point. During sudden changes in irradiance, the INC algorithm responds faster and more accurately.

The INC algorithm performs better in terms of; Response speed, Stability, Minimizing oscillations around the maximum power point. The P&O algorithm is simpler to implement but suffers from oscillations, especially under rapidly changing conditions.

B. Interpretation of the results (Output):

It is clear that both algorithms effectively track changes in power in response to variations in solar irradiance. The INC algorithm shows more stability and smoothness, while the P&O algorithm exhibits some oscillations around the maximum power point. During sudden changes in irradiance, the INC algorithm responds faster and more accurately.

The INC algorithm performs better in terms of; Response speed, Stability, Minimizing oscillations around the maximum power point. The P&O algorithm is simpler to implement but suffers from oscillations, especially under rapidly changing conditions.

II.8. Conclusion

This chapter delves into the core of Maximum Power Point Tracking (MPPT) techniques, which are essential for enhancing the efficiency of photovoltaic (PV) systems. MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (INC), enable the system to continuously adapt to changing environmental conditions such as solar irradiance and temperature by dynamically adjusting operating parameters. These algorithms aim to ensure that the solar panels operate at their optimal point, where maximum power is extracted. Consequently, MPPT techniques mitigate the impact of environmental fluctuations, significantly improving energy conversion efficiency and maximizing the power output of the PV system.

Chapter III.
Cuckoo Search and
Kalman Filter
MPPT algorithms
for PV system

III.1. Introduction

One of the fundamental challenges in controlling dynamic Systems particularly in applications relying on renewable energy sources such as photovoltaic (PV) systems is dealing with incomplete or constantly changing data. Information available about the system is often imprecise due to fluctuations in solar irradiance, measurement noise, or the inherent difficulty in constructing an accurate mathematical model that fully captures the system's behavior.




In this context, advanced algorithms have emerged to handle such uncertainty, notably the Kalman Filter (KF), which employs a dynamic statistical model to fuse measured data with internal system predictions. This approach allows for optimal state estimation while minimizing the effect of noise. The Kalman Filter is particularly effective in systems that can be accurately modeled mathematically and where noise follows a known probabilistic distribution.

On the other hand, the Cuckoo Search (CS) algorithm represents an intelligent optimization technique inspired by the brood parasitic behavior of certain cuckoo species. It relies on random search mechanisms, particularly Lévy flights, to explore the solution space. In Maximum Power Point Tracking (MPPT) applications, the CS algorithm is used to identify the optimal operating voltage that maximizes power output from PV systems, without requiring a precise mathematical model or prior assumptions about measurement noise.

This chapter presents a comparative study between the KF and CS algorithms in the context of MPPT. It begins with a theoretical foundation for each algorithm, followed by an explanation of their design and practical implementation in MPPT systems. The chapter concludes with a performance evaluation under dynamic operating conditions, aiming to highlight the strengths and limitations of each approach and to identify the scenarios in which each algorithm excels in maximizing solar energy extraction.

III.2. Kalman application domain

The Kalman Filter is widely used in systems that require accurate estimation of a state that changes over time, especially when measurements are noisy or imprecise. Its main areas of application include:

-  Automatic control and robotics: For accurate estimation of position and velocity of robots or unmanned aerial vehicles.
-  Navigation and positioning (GPS/INS): To fuse GPS data with inertial navigation systems (INS) for more accurate location tracking.
-  Communication systems: For signal filtering, noise prediction, and improved data reception.

- ✚ Electrical engineering and energy: in MPPT for photovoltaic system and smart grid monitoring.
- ✚ Computer vision and object tracking: To predict the motion of objects in videos or images.

III.3 Kalman Filter

Formulated by *Rudolph Kalman* in 1960, the Kalman filter consists on equations that recursively provide a solution for the least squares method. The Kalman Filter is very popular because of the good results presented in various areas of knowledge.

The use of the Kalman Filter is due to the prediction of a future state, even in the absence of a mathematical model, by means of present and past estimates. Estimates in the Kalman Filter are performed by combining two steps: **Prediction and Correction**. Each step has its own sets of equations.

$$\bar{x}_k = A.x_{k-1} + B.u_{k-1} \quad (III.1)$$

Where: \bar{x}_k is the estimated state in the predicted iteration k from the previous iteration. x_{k-1} the rectified state in the iteration $k-1$ found by the output measure z_{k-1} . u_{k-1} is the control process of the $k-1$ iteration process. A is the transition state constant model used for the previous state. B a constant that depends on the model that is used in the control process. The second equation of the prediction step is used to project the next covariance error.

$$\begin{aligned} x_k &= \bar{x}_k + K_k (z_k - C.\bar{x}_k) \\ H_k &= (I - H_k.C)H_k^- \end{aligned} \quad (III.2)$$

Where: Q is the covariance process related to the noise state matrix. H_k^- the covariance a priori for the k iteration. H_{k-1} the covariance error a posteriori for iteration $k-1$. The second step (correction) aims to correct the value predicted by the prediction step.

The first equation of this step calculates the K gain.

$$K_k = H_k^- . C^T (C.H_k^- . C^T + R)^{-1} \quad (III.3)$$

Next, the estimate x_k is updated via output z_k .

$$x_k = \bar{x}_k + K_k (z_k - C.\bar{x}_k) \quad (III.4)$$

And finally, the last equation that updates the covariance error.

$$H_k = (I - H_k.C)H_k^- \quad (III.5)$$

Where: x_k is the corrected state at iteration k due to z_k output. H_k the covariance of the error a posteriori in the iteration k . K_k the Kalman gain. R covariance of noise. z_k the measurement. C a constant related to the Kalman Filter system and the observed space.

III.4 Kalman Filter MPPT

The diagram depicts a Boost converter-based MPPT system using a Kalman Filter for control.

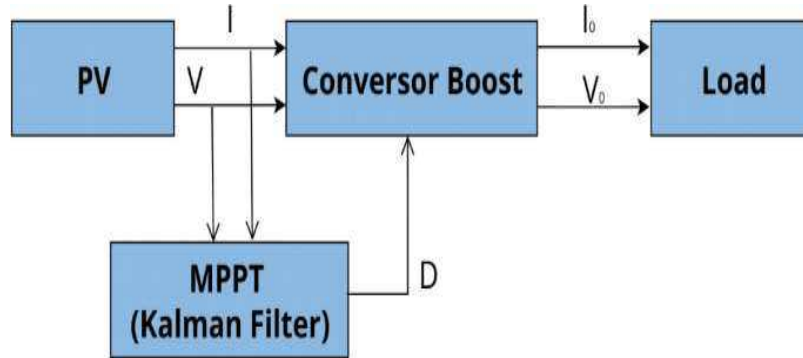


Figure (III.1): MPPT Algorithm using the Kalman Filter

To determine the MPP using a Kalman Filter, the filter must be designed to estimate the maximum power voltage. As evident from the Power-Voltage (P-V) curves in Fig III-2 and III-3, power increases with a positive slope until reaching the optimum point, after which it decreases with a negative slope. Based on this analysis, mathematical equations can be formulated to predict the MPP voltage.

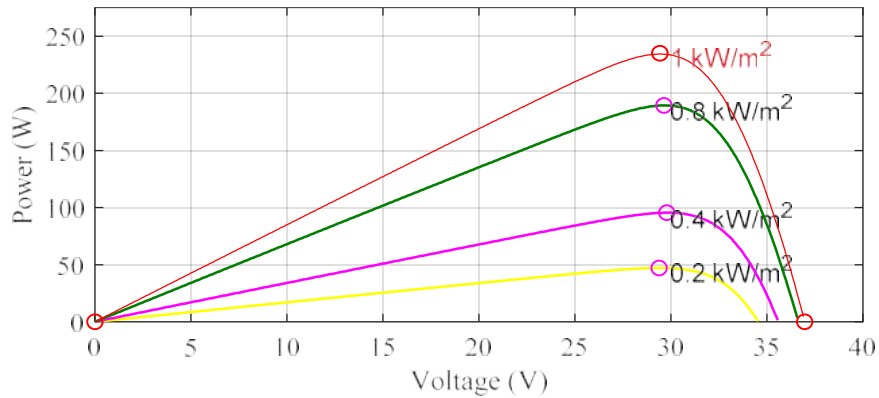


Figure (III.2): PV (P – V) curve for irradiation variable

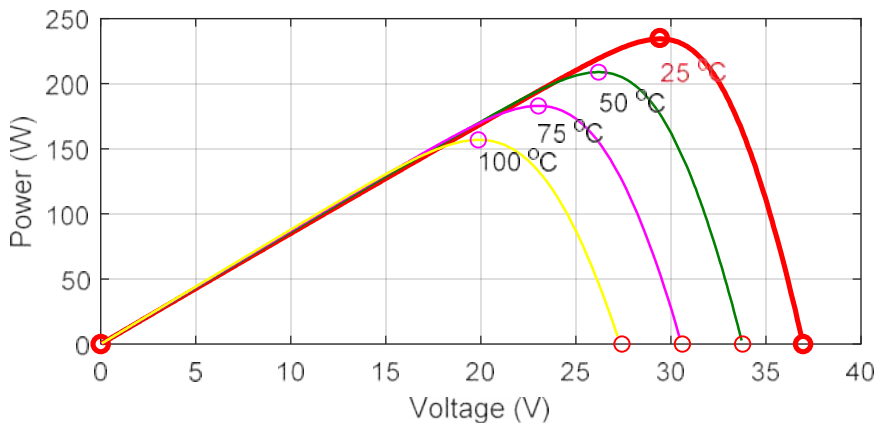


Figure (III.3): PV (P – V) curve for temperature variable

As Kang and Park (2011) considers $A = 1$ and $B = M$, so the equations of the prediction step are:

$$V_k^- = V_{k-1} + M \frac{\Delta P}{\Delta V} \quad (III.6)$$

$$H_k^- = H_{k-1} + Q \quad (III.7)$$

Where: V_k^- is the estimated voltage value by the MPPT using the Kalman filter in the k iteration and corresponds to x_k^- . M equivalent to B and is considered a scaling factor. $\frac{\Delta P^{k-1}}{\Delta V^{k-1}}$ the slope of the curve (P-V) in the iteration $k-1$ and equivalent to the control u_{k-1} .

The correction step process is made it as follows. According to Kang and Park (2011), the K gain can be calculated adopting $C = 1$ and by the covariance error as eq(III.5):

$$K_k = H_k^- (H_k^- + R)^{-1} \quad (III.8)$$

The equations eq(III.6) and eq(III.7) of the correction step corrects the predicted covariance measurement with the PV panel voltage measurement $V_{photovoltaic,k}$ as follows:

$$V_k = V_k^- + K_K * (V_{photovoltaic,k} - V_k^-) \quad (III.9)$$

$$H_k = (1 - K_K) * H_k^- \quad (III.10)$$

Where: V_k is the value of the corrected voltage using the Kalman filter based MPPT in the k iteration provided by the $V_{photovoltaic,k}$ PV voltage measurement (Kang and Park (2011)).

The flowchart of the Kalman Filter-based MPPT algorithm is presented in Fig.III.4.

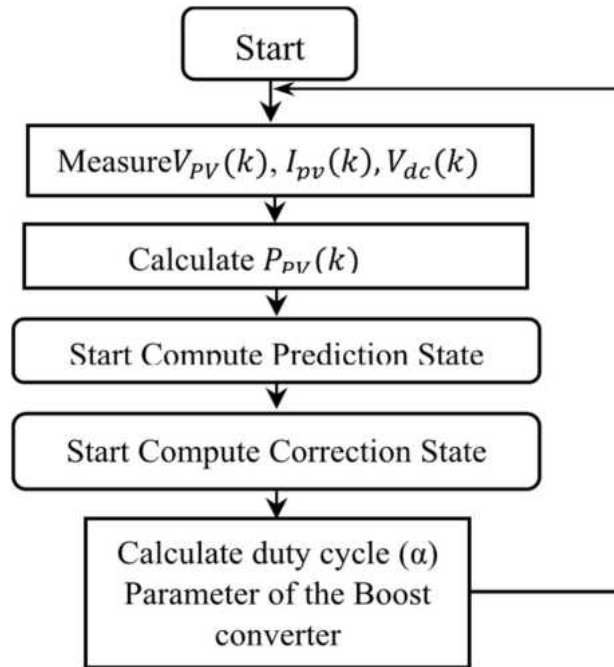


Figure (III.4): Flowchart of the KF MPPT method.

III.5. Cuckoo Search Methods

The Cuckoo Search algorithm is an optimization algorithm developed by *Xin-She Yang* and *Suyash Deb* in 2009. It was later found to be a special case of the well-known $(\mu + \lambda)$ evolution strategy. This algorithm is inspired by the obligate brood parasitism behavior exhibited by some species of cuckoos, where they lay their eggs in the nests of other bird species, leaving the host birds to raise their young. In some instances, host birds may directly confront the parasitic cuckoos; if they detect that the eggs are not their own, they may throw the foreign eggs out or abandon the nest altogether to build a new one elsewhere. Certain cuckoo species, such as the taper a cuckoo in the new world, have evolved sophisticated parasitic strategies. The females of these species can accurately mimic the color and pattern of the eggs of specific host birds.

III.6. Application Domain CS

The Cuckoo Search Algorithm (CS) is widely used in various scientific and engineering fields due to its efficiency in solving complex and nonlinear optimization problems. Below are the main application areas:

- ❖ Renewable Energy: Maximum Power Point Tracking (MPPT) in solar panels and enhancing the efficiency of wind and hybrid energy systems.
- ❖ Communications: Optimizing packet routing in wireless networks, Resource allocation in 5G networks and MIMO system design.
- ❖ Engineering Design: Design optimization in mechanical and civil engineering.

III.7 Cuckoo search (CS) uses the following representations

Each egg in a nest represents a solution, and a cuckoo egg represents a new solution. The aim is to use the new and potentially better solutions (cuckoos) to replace a not-so-good solution in the nests.

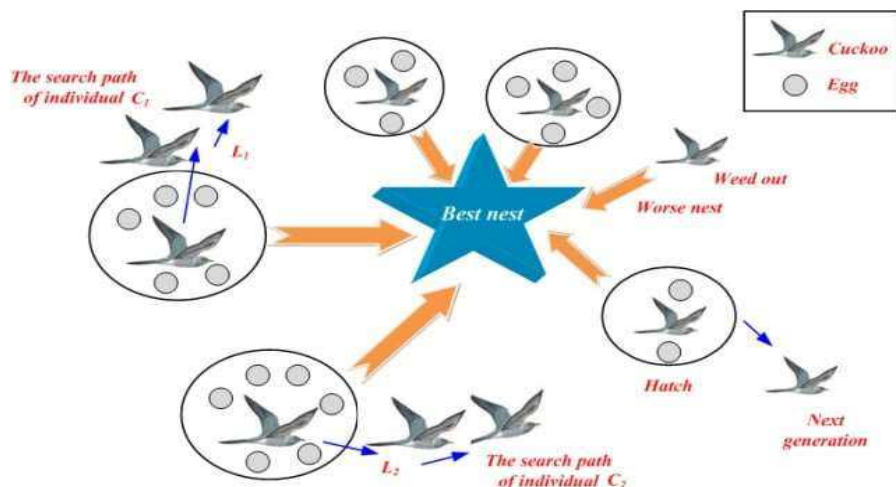


Figure (III.5): Number of available host nests is fixed.

In the simplest form, each nest has one egg. The algorithm can be extended to more complicated cases in which each nest has multiple eggs representing a set of solutions. CS is based on three idealized rules:

- Each cuckoo lays one egg at a time, and dumps its egg in a randomly chosen nest;
- Each cuckoo lays one egg at a time, and dumps its egg in a randomly chosen nest;
- The number of available hosts nests is fixed, and the egg laid by a cuckoo is discovered by the host bird with a probability $P_a \in (0,1)$. In this case, the host bird can throw the egg away/abandon the nest, and build a completely new nest.

III.8. Steps of the Cuckoo Search Algorithm

The steps of the cuckoo search algorithm.

- 1) **Initialization:** Cuckoo birds prefer to lay their eggs in the nests of other birds.
- 2) **Levy Flight:** It is a random flight or walk. The steps are defined in terms of step lengths that have a certain probability distribution with random directions. This type of flight is observed in different animals and insects. The following movement is determined by the current position.

$$X^{t+1}_i = X^t_i + \alpha \cdot \text{levy}(\lambda) \quad (\text{III.11})$$

- 3) **Fitness Calculation:** Calculation of fitness is achieved by using the fitness function to find the best solution. Nest is chosen randomly. The fitness of the cuckoo egg (new solution) is then compared to that of the host eggs (solutions) in the nest. If the value of the cuckoo egg's fitness function is less than or equal to the value of the randomly chosen nest's fitness function, the randomly chosen nest is replaced by the new solution.
- 4) **Termination:** The fitness function compares the solutions in the current iteration and only the best solution is passed further. If the number of iterations is less than the maximum, the best nest is retained. All cuckoo birds are ready for their next actions after completing the initialization, levy flight, and fitness calculation processes. The cuckoo search algorithm will be terminated once the maximum number of iterations has been reached. These steps are applicable to any optimization problem. In such cases, each cuckoo egg and cuckoo nest play an important role.

III.9 Random Exploration and step size

One of the key aspects of the Cuckoo Search algorithm is the use of Lévy flights or random walks to generate new solutions. The update rule is typically written as:

$$X_{t+1} = X_t + S * E_t \quad (\text{III.12})$$

where:

X_t is the current solution.

E_t represents the change, which is drawn either from a Gaussian distribution (in the case of a random walk) or a Lévy distribution (in the case of Lévy flights).

S is the step size, which determines how far the algorithm moves from one solution to the next.

Lévy flights allow for larger and more unpredictable jumps, which help the algorithm explore the search space more effectively. However, choosing an appropriate step size (s) is crucial:

- If S is too large, the new solution might be too far from acceptable bounds or even outside the feasible search space.
- If S is too small, the changes will be minimal and the search may get stuck in local optima.

Therefore, tuning the step size is important to strike a balance between exploration (searching widely) and exploitation (converging accurately to the best solution).

III.10. MPPT Control Algorithms

MPPT algorithms are designed to find the optimal operating point (voltage and current) on the power-voltage curve of a solar panel, ensuring the maximum power output. These algorithms are crucial for maximizing the energy harvested from solar panels under varying conditions like changing solar irradiance and temperature.

The CS method, short for Cuckoo Search, is a metaheuristic algorithm used for optimizing the Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems, especially under partial shading conditions. It helps find the maximum power point (MPP) by simulating the reproductive behavior of cuckoo birds, where nests are randomly updated, and some nests are replaced with new, potentially better solutions.

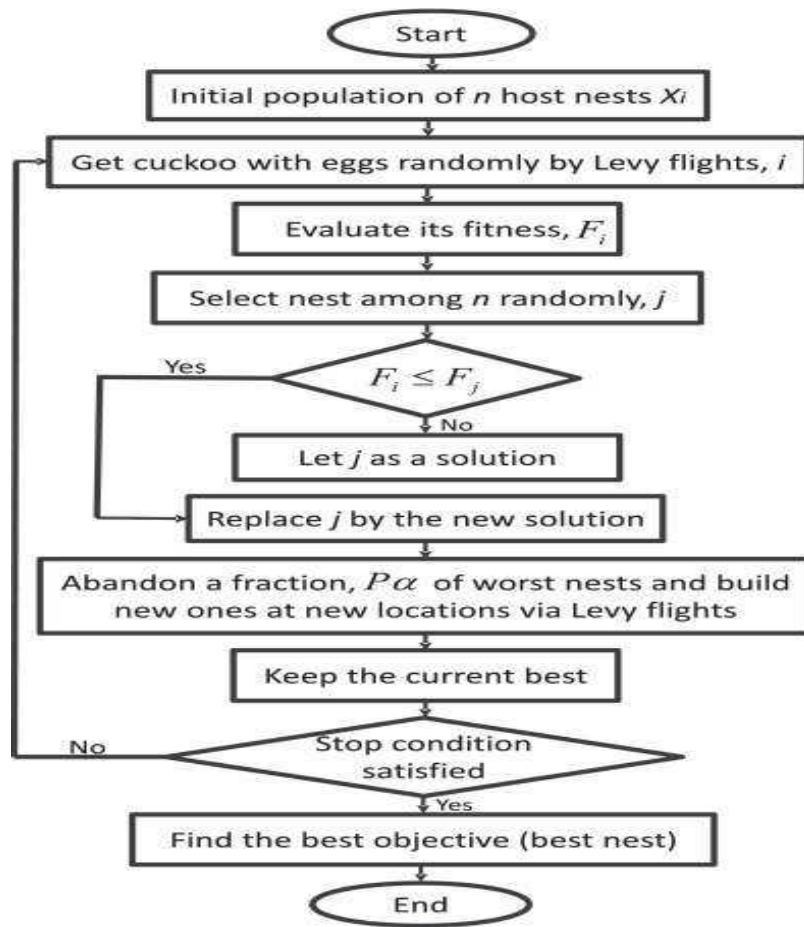


Figure (III.6): Flowchart of Variable step size CS MPPT method.

III.11. Simulation Results

III.11.1. Influence of Irradiance with Constant Temperature

The following figures represent the results of the PV panel for the contrast in the case of variable irradiance and constant temperature ($T = 25^{\circ}\text{C}$):

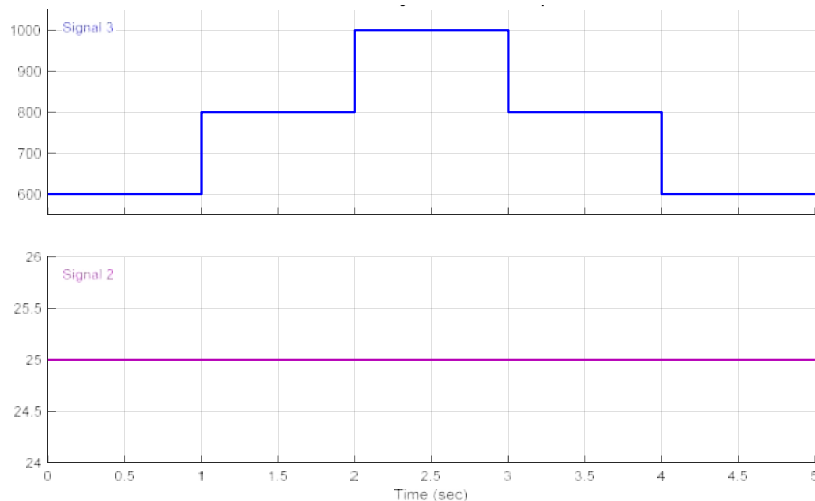


Figure (II.7): Signal Builder for Variable Illumination and Constant Temperature.

❖ KF and CS Algorithm input

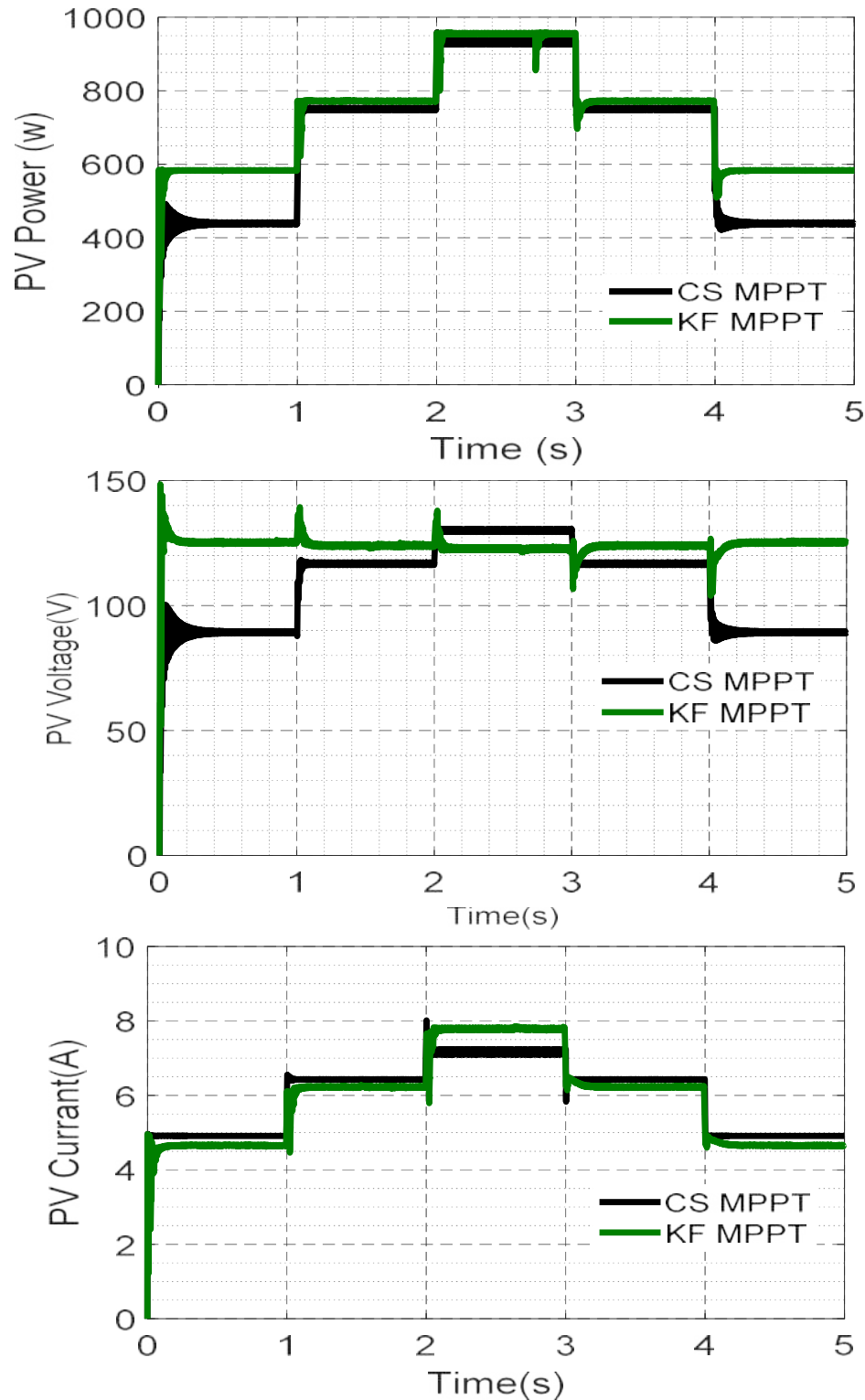


Figure (III.8): Simulation Results of the PV for Variable Irradiance and ($T=25^{\circ}\text{C}$).

❖ KF and CS Algorithm output

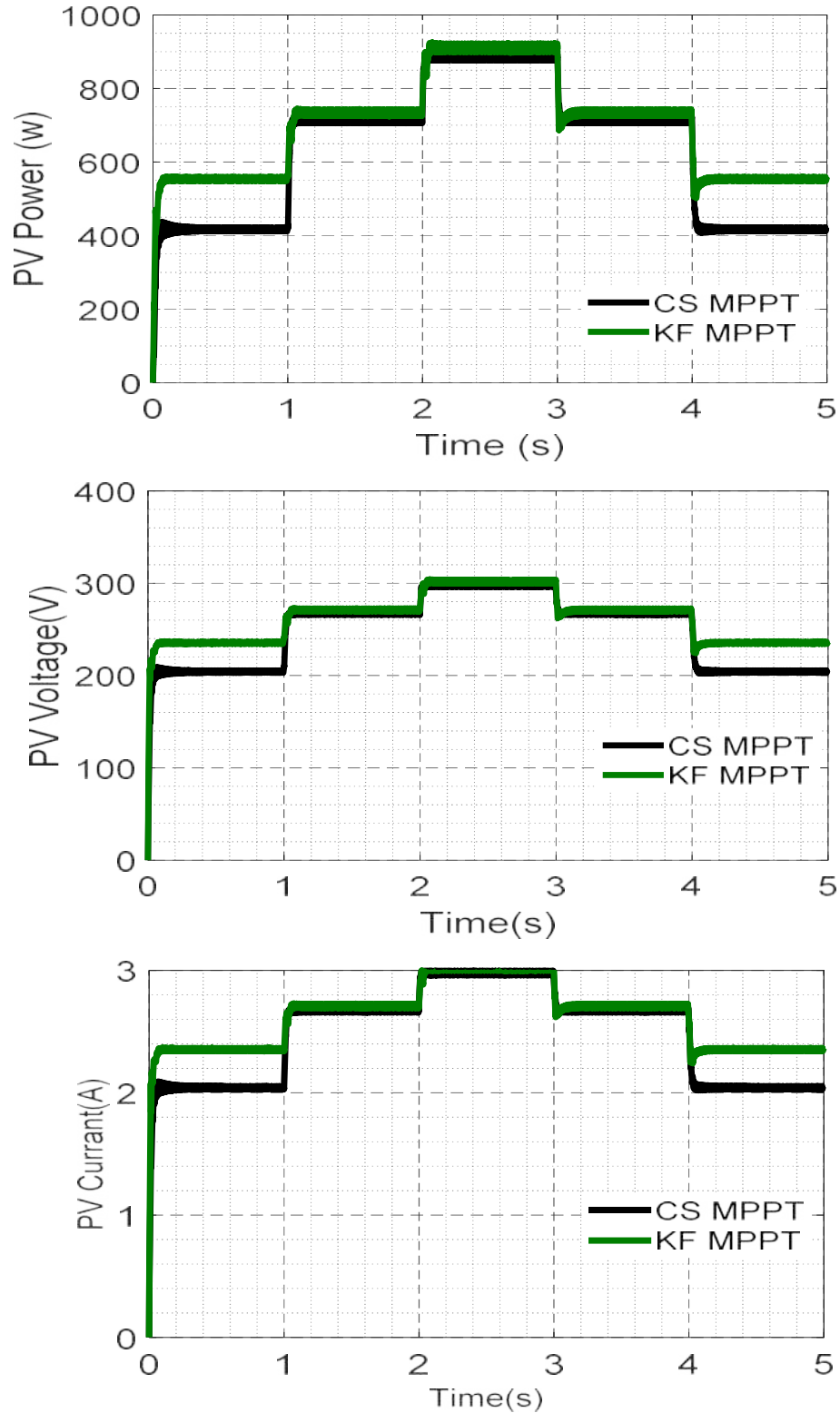


Figure (III.9): Simulation Results of the PV for Variable Irradiance and ($T=25^{\circ}\text{C}$).

This section investigates the impact of varying irradiance levels on the performance of the PV panel while maintaining a constant temperature of 25°C (Fig.III.7).

The fig. (III.8) and fig. (III.9) illustrate the simulation results obtained for both KF and CS MPPT methods. The voltage, current, and power (output and input) of the PV system exhibits gradual variations across different time intervals, reflecting dynamic changes in solar irradiance or system conditions. While the Kalman Filter (KF) MPPT demonstrates superior tracking speed and overall responsiveness, the Cuckoo Search (CS) MPPT achieves marginally better performance under specific operating conditions, suggesting a trade-off between rapid adaptation and steady-state efficiency.

III.12. Comparison of the different technique MPPT

Various traditional and intelligent MPPT methods are used to determine the Maximum Power Point (MPP) using algorithms such as PO (Perturb and Observe), KF (Kalman Filter), INC (Incremental Conductance), and CS (Cuckoo Search).

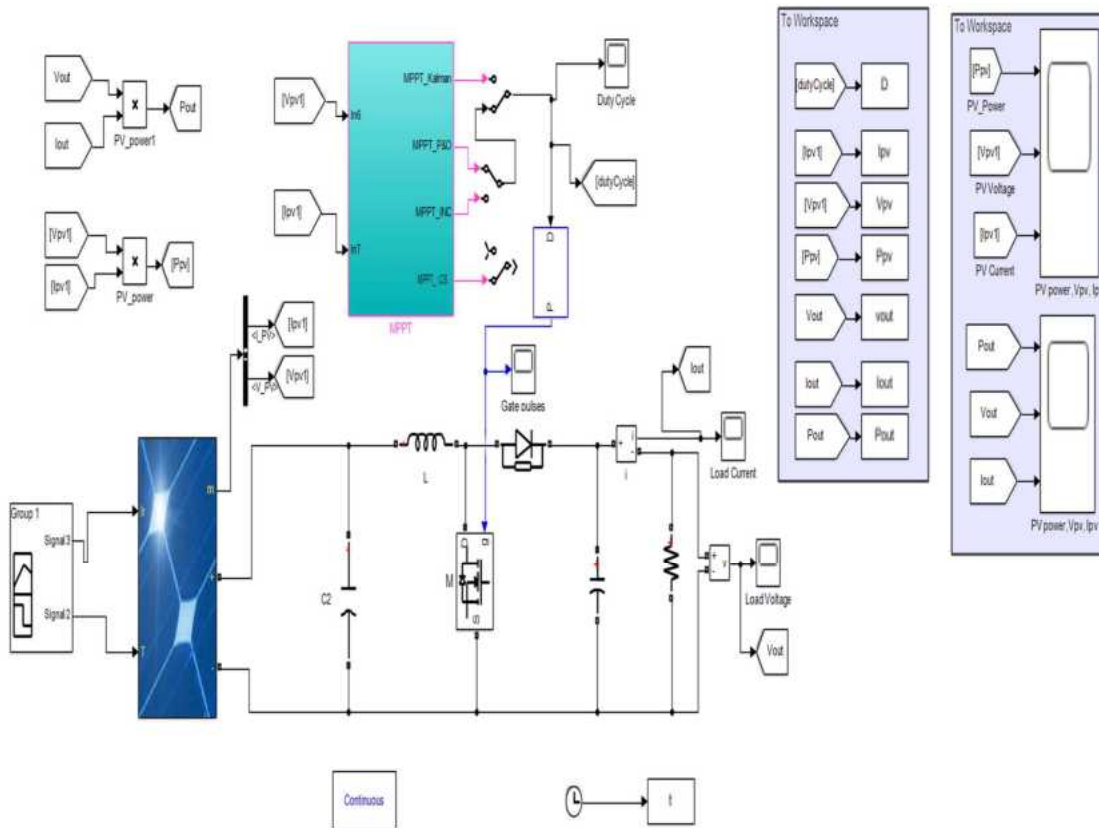
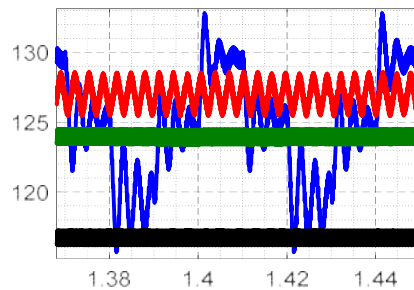
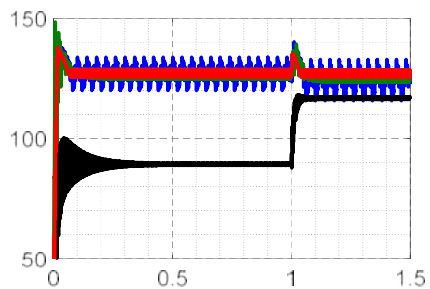
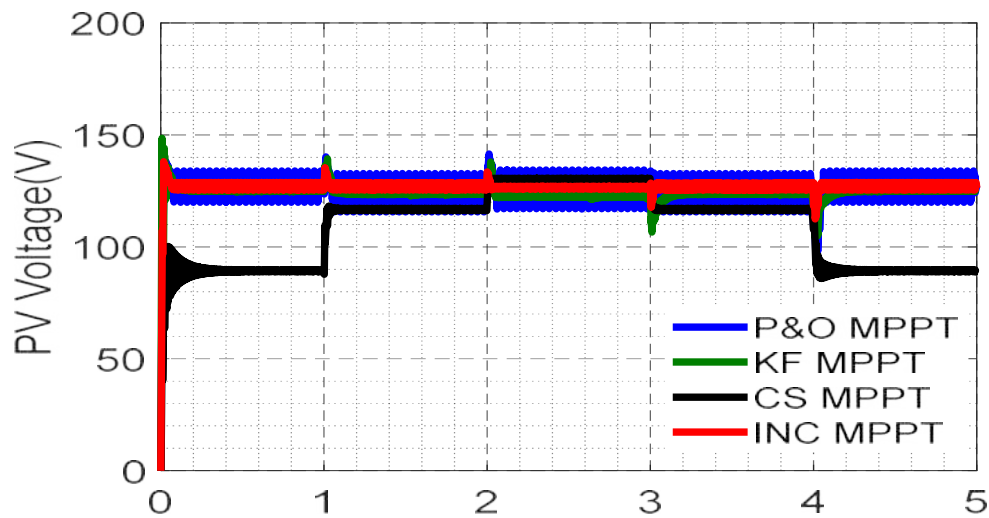
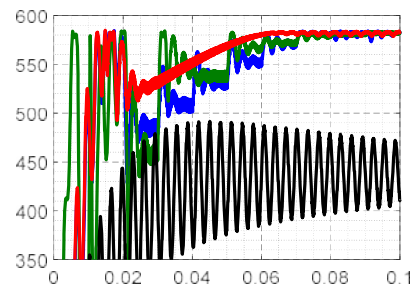
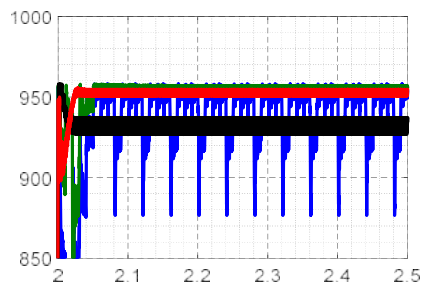
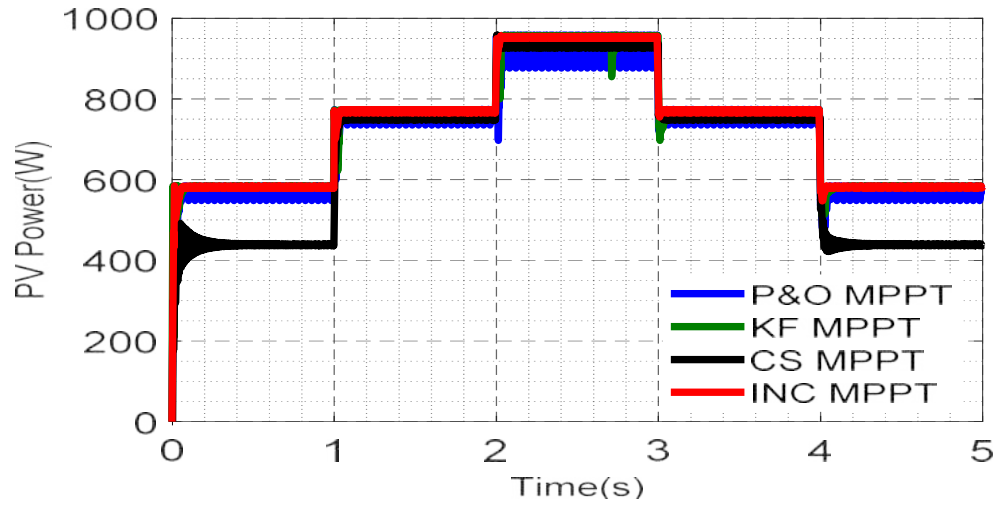


Figure (III.10): Block diagram of a photovoltaic system by the MPPT (P&O- INC- KF- CS).

❖ Comparison of MPPT- P&O- INC- CS-KF (Input PV)



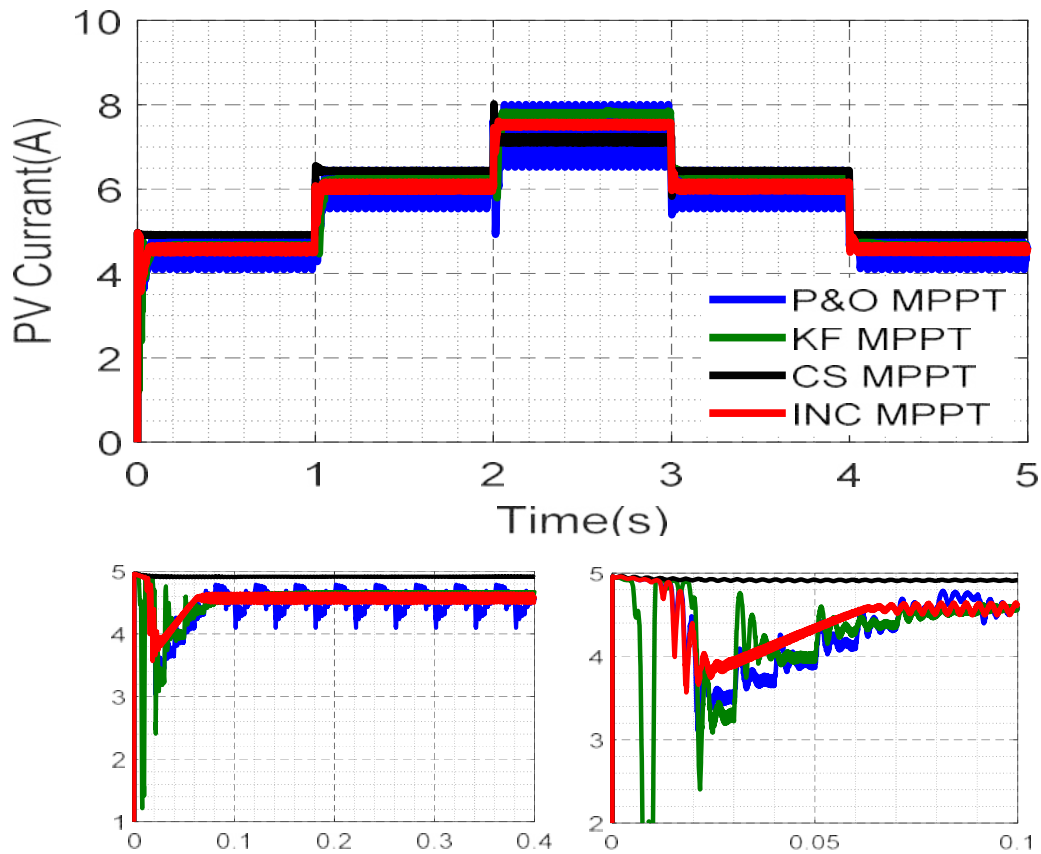
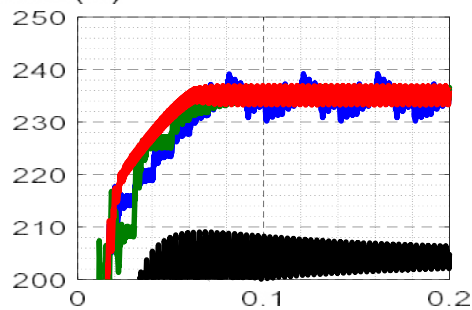
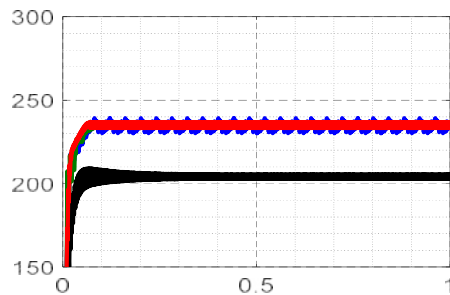
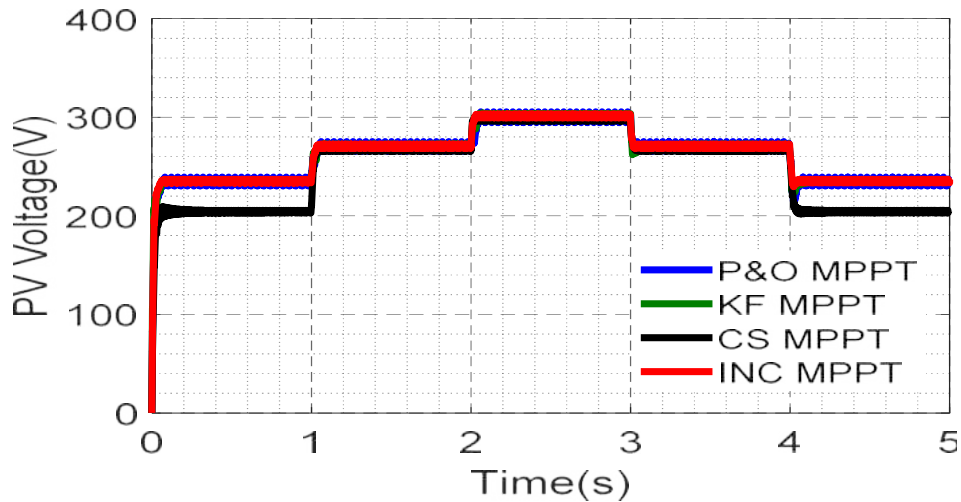
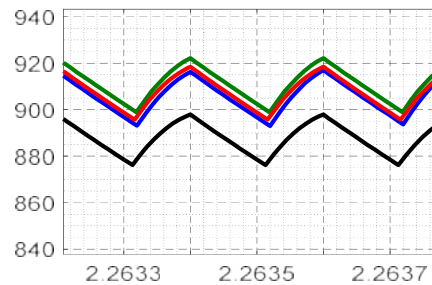
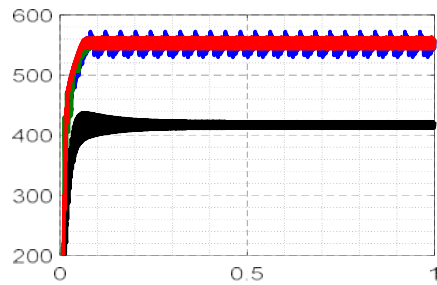
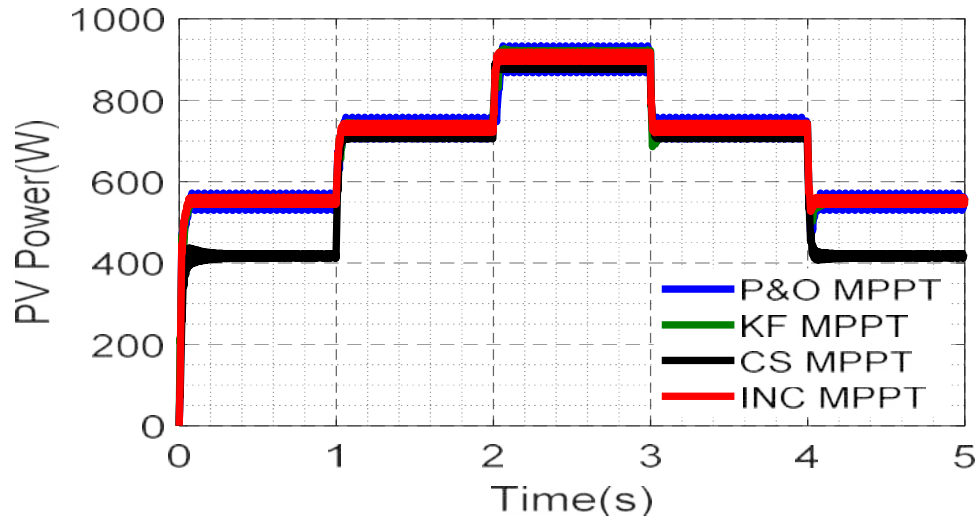


Figure (III.11): Comparison different MPPT techniques.

The response of the photovoltaic system in terms of power, voltage, and current (Fig. III.11 and 12), under the application of different MPPT algorithms (P&O, INC, CS, KF), reveals clear performance variations under changing irradiance conditions. The Kalman Filter (KF) algorithm demonstrated a high capability in tracking the Maximum Power Point (MPP), achieving rapid convergence with stable and low-oscillation power profiles across all irradiance levels, indicating excellent dynamic behavior and high tracking accuracy. It is followed by the Incremental Conductance (INC) algorithm, which also achieved fast convergence, although with slightly higher oscillations compared to KF.

In contrast, the Perturb and Observe (P&O) algorithm exhibited noticeable oscillations around the operating point, particularly under steady-state conditions, leading to reduced tracking accuracy and a decrease in the extracted current compared with more advanced methods. The Cuckoo Search (CS) algorithm showed relatively weaker performance, especially at low irradiance levels, where it displayed high sensitivity to sudden irradiance changes and required frequent re-adjustment. This resulted in unstable tracking and lower-quality outcomes relative to the other algorithms.

❖ Comparison of MPPT- P&O, INC, CS and KF (Boost Output)



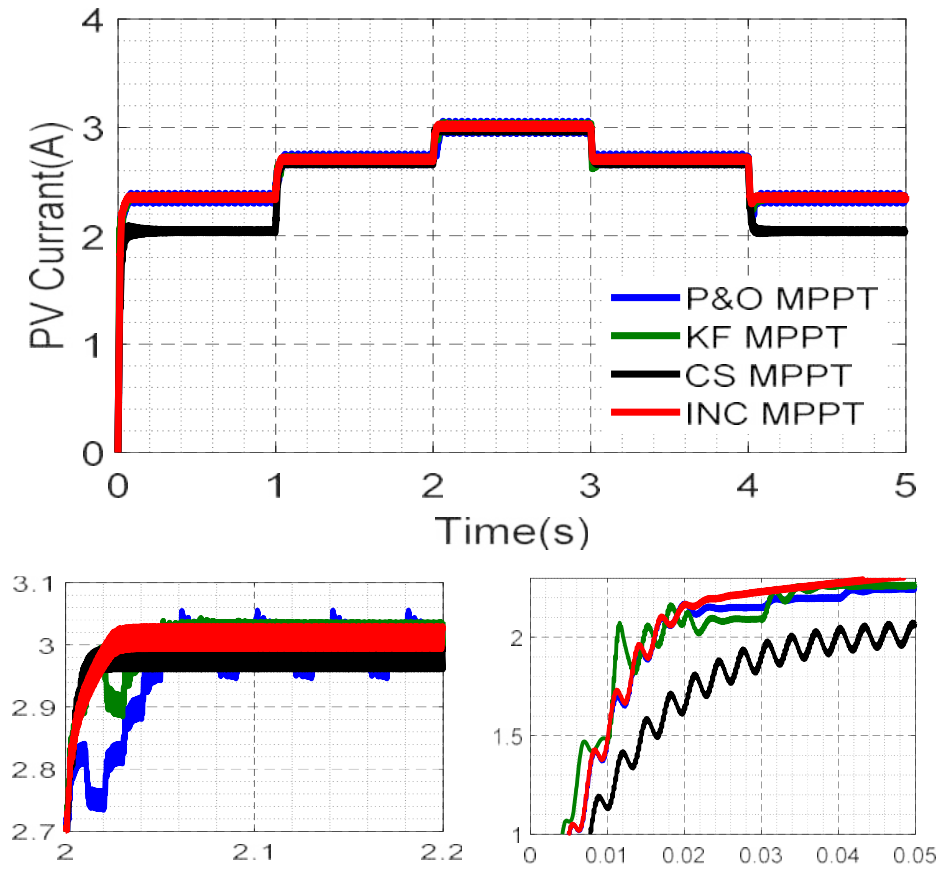


Figure (III.12): Comparison methods for the different condition.

III.13 Conclusion

In this work, the Kalman Filter, Incremental Conductance (INC), Perturb and Observe (P&O), and Cuckoo Search (CS) algorithms were designed and simulated to evaluate their performance in estimation and optimization, particularly under noisy conditions and complex operating scenarios. The Kalman Filter demonstrated superior capability in accurately estimating system variables within dynamic environments, while the INC algorithm showed reliable tracking performance with rapid convergence. Conversely, the P&O and CS algorithms exhibited limitations—P&O due to its steady-state oscillations, and CS due to its sensitivity to irradiance variations and the need for frequent re-tuning. Overall, the results emphasize the importance of selecting the most suitable MPPT algorithm based on system characteristics and operational requirements to ensure optimal performance and robustness.

General Conclusion

This study highlights the importance of photovoltaic (PV) solar systems as one of the promising and sustainable solutions to address modern environmental and energy challenges. By tracing the development of this technology and examining its current state, it becomes clear that there is significant potential for its utilization, especially with the notable advancements in solar cell design and improvements in connection and operation methods.

Maximum Power Point Tracking (MPPT) techniques have proven to play a crucial role in enhancing the efficiency of PV systems. Algorithms such as Incremental Conductance (INC) and Kalman Filter (KF) demonstrated superiority in terms of accuracy and stability, making them the preferred choice in environments with rapidly changing conditions. Although the Cuckoo Search (CS) algorithm is relatively slower, it has shown high effectiveness in approaching optimal solutions.

Simulation results and comparisons indicate that combining the precision of intelligent algorithms with fast response times may represent the future of MPPT development, encouraging further research into hybrid algorithms that balance performance and efficiency.

In light of these findings, it is essential to support research and development efforts and adopt policies that promote the use of PV solar energy—not only for its environmental and economic benefits but also as part of a national strategy for transitioning toward clean and sustainable energy.

Bibliographiques

- [01]. Yehia Lalili, Commande MPPT d'un système photovoltaïque sous irradiation uniforme et non-uniforme, Mémoire de Fin d'étude pour l'obtention du Diplôme Master en Automatique, Option: Automatique et Systèmes, Université Mohammed Seddik Benyahia – JIJEL, 2020/2021.
- [02]. F. HEROGUEL, "Les Cellules Photovoltaïques," Ecole Normale Supérieure, Lyon, Epreuve de projet, 2007.
- [03]. BEHIR Boubaker - KHEMIDA Fathi et GUETROUNE Kheir eddine, Optimisation d'un système photovoltaïque adapté par une commande MPPT floue, , Mémoire de Fin d'étude pour l'obtention du Diplôme Master en Automatique, Option: Réseaux électriques, L'Université Echahid Hamma Lakhdar d'El Oued, 2019.
- [04]. M. Hatti, « Contrôleur Flou pour la Poursuite du Point de Puissance Maximum d'un Système Photovoltaïque », JCGE'08, Lyon, 2008.
- [05]. <https://www.clicours.com/lenergie-solaire-photovoltaïque/>, 23/02/2023, 14 :10.
- [06]. I.Zemghassene "Recharge d'une batterie avec un panneau photovoltaïque et poursuite de point de puissance maximale" Master académique en Automatique UMMTO 2018.
- [07]. N.Berreziga, S.Babou, « commande directe par la méthode incrémentale conductance (IncCond) d'un panneau photovoltaïque » Master en électrotechnique Université de Tizi-Ouzou septembre 2018.
- [08] Hadji Slimane Thèse de doctorat "Optimisation de la conversion énergétique pour les systèmes à énergie photovoltaïque" Université Ferhat Abbas de Sétif octobre 2018.
- [09] S.Arab – D.Toudert "Etude d'un Système Photovoltaïque" Mémoire de fin d'études en vue d'obtention Master académique Université de Tizi-Ouzou 2017.
- [10] M. BERROUBI Abdennoure "Commande par mode de glissement des convertisseurs Buck et Boost intégrés dans un système photovoltaïque" Mémoire Master en génie électrique
- [11] AKHAM Amel BENSAAD BAKHTA Soulef, Modélisation, simulation et commande d'un Système Photovoltaïque, Master académique en Electronique Spécialité : Instrumentation, Université El-wancharissi de Tissemsilt, 2021.
- [12] <http://www.solarserver.de/?gclid=CJWA1ruS-K4CFS4NtAodSzY7xw>.

- [13] BENSACI Wafa , «Modélisation et simulation d'un système photovoltaïque adapté par une commande MPPT », mémoire de master, Université Kasdi Merbah–Ouargla, 2012.
- [14] BOUALEM, DENDIB, « Technique conventionnelles et avancée de poursuite MPPT pour des applications photovoltaïque : étude comparative », mémoire de magister, Université Ferhat Abbes–Sétif, 2007.
- [15] M.BEDRANE Farid. Etude comparative entre quelques méthodes de poursuite du point de puissance maximale dans les systèmes photovoltaïques. Université Abderrahmane MIRA de Bejaia
- [16] Ogbi Zoulikha, « Mesure automatisée du spectre d'absorption optique des cellules solaires », mémoire de master, Université Med khider Biskra ,2014.
- [17] BENADEL Faiza. Etude Et Simulation D'une Commande MPPT Pour Système PV. UNIVERSITE MOHAMED BOUDIAF - M'SILA
- [18] M. Dietschy, «Les cellules photovoltaïques», cours classes préparatoires CPE, Institution des Chartreux Année 2004-2005
- [19]. M. SLAMA Fateh, « Modélisation d'un système multi générateurs photovoltaïque interconnectées au réseau électrique», mémoire de magister, Université Ferhat Abbes –Sétif ,2012.
- [20] HAKOUMI Ahmed, BENAMAR Abdeldjalil, Commande MPPT et contrôle d'un système photovoltaïque 3KW par la logique floue, Mémoire De: Master En Electrotechnique Option: Commande Electrique, Université Ahmed Draia Adrar, 2019.
- [21] <https://www.algerie-eco.com/2018/04/04/energie-solaire-lalgerie-enfin-determinee-a-exploiter-son-enorme-potentiel/>, 25/02/2023, 16 :53.
- [22] ZIAT Soheir Ibtisse, MEDJAHED nour el houda, Modélisation et simulation d'un système photovoltaïque commandé par la commande MPPT (P&O), Master en : Domaine: Science et Technologie Filière : Electromecanique Spécialité : Electromecanique, Centre Universitaire Belhadj Bouchaib d'Ain-Temouchent, 2019/2020.
- [23] F.Z. ZERHOUNI, M. ZEGRAR et A. BOUDGHENE STAMBOULI ;"Connexion directe source d'énergie renouvelable verte non polluante photovoltaïque à une charge", Revue des Energies Renouvelables Vol. 12 N°4 (2009) 585 – 595.
- [24] Y. LALILI;" Commande MPPT d'un système photovoltaïque sous irradiation uniforme et non-uniforme", Mémoire de Master, Université Mohammed Seddik Benyahia-JIJEL, 2020/2021.

- [25] CH. WASSILA FAIZA; "Réalisation d'une commande buck-boost pour PV", Mémoire de Master, Université Abou Bakr Belkaid Tlemcen, 2017-2018.
- [26] : M me. BELOUNIS Ouassila, Réglage par contrôleur flou d'un entraînement électrique un hacheur à GTO-MCC », Memoire De Fin D'etudes en vue de L'obtention Du Diplome D'ingenieur D'etat En Genie Electrotechnique, UNIVERSITE DE M'SILA, 2008/2009.
- [26] M. ALAYAT, I. BOUCETTA; " Maximisation de la production d'un système photovoltaïque à base de MPPT soumis à des éclairagements différents", Mémoire de Master, Université Badji Mokhtar Annaba, juin 2017.
- [27] A.BELKAID; "Conception et implémentation d'une commande MPPT de haute performance pour une chaîne de conversion photovoltaïque autonome", Thèse de Doctorat en sciences, Université Ferhat Abbas-Setif1, 19/10/2015.
- [28] M.HACID, L.KACI;" Caractérisation et commande d'un système photovoltaïque", Mémoire de Master, Université Mouloud Mammeri de TIZI-OUZOU, 2021.
- [29] O.M. BOUKLI-HACENE; "Conception et Réalisation d'un Générateur Photovoltaïque Muni d'un Convertisseur MPPT pour une Meilleure Gestion Energétique", Thèse de Magister, Université Abou Bakr Belkaid-Tlemcen, 2011.
- [30] M. S. BENSAOUDI, S E. ARAR;"Etude d'un convertisseur boost pour système photovoltaïque", Mémoire de Master, HIGHER SCHOOL IN APPLIED SCIENCES Tlemcen, 2020.
- [31] N. AOUCHICHE;" Conception d'une commande MPPT optimale à base d'intelligence artificielle d'un système photovoltaïque", Thèse de Doctorat, Université Bourgogne Franche-Comté, 2020.
- [32] A. MAHAMMEDI;" Contribution to the control of a Power Converter with Improved Topologies Associated with a Photovoltaic Generator Based on Advanced Techniques", Thèse de Doctorat en sciences, Université Ziane Achour-Djelfa, 2020.
- [33] L. TARGANT, S. KHALEF; " Modélisation et simulation d'un système photovoltaïque connecté au réseau électrique", Mémoire de Master, Université Mouloud Mammeri de TIZI-OUZOU, 2018.
- [34] Kh. Bouchareb, A.Touati; "Modélisation et Simulation d'un système PV adapté par une commande MPPT basée sur un mode glissant", Mémoire de Master, Université 8Mai 1945 – Guelma, 2021.
- [35] : H. BUHLER" Réglage par logique floue " -Presse polytechniques et universitaires – 1994.
- [36] : Walid, A. B. I. (2019). Commande floue pour l'optimisation de la puissance d'un générateur photovoltaïque (Doctoral dissertation, UNIVERSITE MOHAMED BOUDIAF-M'SILA)

[37] : Boudia, A. (2020). Contribution à l'étude d'un système photovoltaïque connecté au réseau électrique avec un système de stockage à base d'une inductance supraconductrice (SMES) (Doctoral dissertation, Univ M'sila).

[38] : K. Khettab, « Techniques avancées pour la synthèse et l'amélioration des performances des systèmes de commande adaptative d'ordre fractionnaire pour les processus incertains ». Thèse de doctorat, Université de Skikda – 2016.