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Presented by:

1. **KADDOURI Mohammed Djilani.**
2. **OUDINI Abdechafi**
3. **GHEDEIR MOHAMMED Salah eddine**

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Dr. Fateh Bekkat	**Chairman**
Dr. Ali Bebboukha	**Supervisor**
Dr. Abderrahman Ben Hamza	**Examiner**

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الملخص:

تُعد الخلايا الكهروضوئية من أبرز تقنيات الطاقة المتجددة، حيث تُحوِّل الطاقة الشمسية إلى طاقة كهربائية وتسهم في الحد من التلوث وتقليل الاعتماد على الوقود الأحفوري. إلا أن أداءها يتأثر بعدة عوامل تشغيلية وبيئية، مثل درجة الحرارة، وشدة الإشعاع الشمسي، والتظليل، وتراكم الغبار، مما ينعكس على كفاءتها وإنتاجيتها. هدفت هذه الدراسة إلى تحليل تأثير هذه العوامل على أداء الألواح الشمسية، مع توظيف خوارزمية Perturb and Observe (P&O) للكشف عن بعض الأعطال الشائعة، وهي: الغبار، والرطوبة، والدارة القصيرة، والأقدمية، والتظليل. وقد أظهرت النتائج أن الرطوبة تُعد أكثر الأعطال تأثيرًا على أداء اللوح الشمسي مقارنةً ببقية الأعطال المدروسة، مما يؤكد أهمية مراقبتها واتخاذ التدابير المناسبة للحد من آثارها وتحسين موثوقية الأنظمة الكهروضوئية.

الكلمات المفتاحية: نظام، طاقة، مولد، كهروضوئي، ضوء الشمس

Abstract:

Photovoltaic cells are among the most prominent renewable energy technologies, converting solar energy into electricity and contributing to pollution reduction and decreased reliance on fossil fuels. However, their performance is affected by several operational and environmental factors, such as temperature, solar radiation intensity, shading, and dust accumulation, which impact their efficiency and productivity. This study aimed to analyze the effect of these factors on solar panel performance, employing the Perturb and Observe (P&O) algorithm to detect some common faults: dust, humidity, short circuits, age, and shading. The results showed that humidity has the most significant impact on solar panel performance compared to the other studied faults, highlighting the importance of monitoring it and taking appropriate measures to mitigate its effects and improve the reliability of photovoltaic systems.

Key words: System, power, generator, Photovoltaic, Sunlight

Résumé:

Les cellules photovoltaïques figurent parmi les technologies d'énergies renouvelables les plus importantes. Elles convertissent l'énergie solaire en électricité et contribuent à la réduction de la pollution et à la diminution de la dépendance aux énergies fossiles. Cependant, leurs performances sont affectées par plusieurs facteurs opérationnels et environnementaux, tels que la température, l'intensité du rayonnement solaire, l'ombrage et l'accumulation de poussière, qui influent sur leur efficacité et leur productivité. Cette étude visait à analyser l'effet de ces facteurs sur les performances des panneaux solaires, en utilisant l'algorithme Perturber et Observer (P&O) pour détecter certains défauts courants : poussière, humidité, courts-circuits, vieillissement et ombrage. Les résultats ont montré que l'humidité a l'impact le plus significatif sur les performances des panneaux solaires par rapport aux autres défauts étudiés, soulignant ainsi l'importance de la surveiller et de prendre les mesures appropriées pour atténuer ses effets et améliorer la fiabilité des systèmes photovoltaïques.

Mots-clés : Système, Puissance, Générateur, Photovoltaïque, Lumière du soleil

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In the name of Allah, the Most Gracious, the Most Merciful. Praise be to Allah, and peace and blessings be upon His Messenger.Guided by the Prophetic saying: "He who does not thank people, does not thank Allah," we are highly honored to express our deepest gratitude and sincere appreciation to our esteemed supervisor, Dr. Ali Beboukha, for accepting to supervise this graduation thesis, and for his patience, invaluable guidance, and insightful technical feedback that illuminated our research path.We would also like to extend our profound respect and appreciation to the honorable members of the examination committee for their valuable time and effort dedicated to evaluating and refining this study.Furthermore, our sincere thanks go to all the faculty members of the Industrial Maintenance Department at the University of El Oued (Echahid Hamma Lakhdar), from whose knowledge we have greatly benefited throughout our academic years.To all of them, and to the ultimate source of our strength—our beloved parents—we dedicate this humble work.

DEDICATION

We dedicate this humble work:[By: Kaddouri Mohamed El Djilani]To my beloved parents, for their endless love, prayers, and sacrifices that brought me to this day. To my dear family, brothers, and sisters, for always being my strength and support.[By: Ghadir Mohamed Salah Eddine]To the lights of my life, my dearest father and mother, whose encouragement and blessings guided my steps. To my beloved family and relatives, for their constant faith in me.[By: Oudini Abdelshafi]To my wonderful parents, the ultimate source of my inspiration, patience, and success. To my dear brothers, sisters, and family, for their unconditional love and presence by my side.[Joint Dedication]To our esteemed professors at the Department of Industrial Maintenance at the University of El Oued, who illuminated our paths with knowledge.To our loyal friends and classmates, with whom we shared unforgettable moments, challenges, and successes throughout this academic journey. To everyone who supported us, we dedicate this

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CHAPTER III: Test and Application

General Introduction

General Introduction

Photovoltaic (PV) cells, commonly known as solar cells, are fundamental components of renewable energy systems, enabling the direct conversion of solar radiation into electrical energy through the photovoltaic effect. Owing to their environmental benefits and their contribution to reducing dependence on fossil fuels, PV technologies have become a key element in the global transition toward sustainable energy production.

The performance of PV cells is strongly influenced by operating and environmental conditions, including solar irradiance, temperature, angle of incidence, shading, dust accumulation, and humidity. Variations in these parameters significantly affect the electrical characteristics and energy output of PV systems. Therefore, understanding the relationship between operating conditions and PV performance is essential for improving system efficiency and reliability.

Among these factors, temperature and solar irradiance are particularly critical. An increase in temperature generally leads to a reduction in the output voltage and overall efficiency of PV cells, whereas changes in solar irradiance directly influence the generated current and power output. In addition, partial shading and surface contamination can further degrade system performance and reduce energy production.

This study investigates the effects of variations in operating conditions, including temperature fluctuations, changes in solar irradiance, shading, and dust accumulation, on the performance of photovoltaic cells. Through a comprehensive analysis of these factors, the research aims to identify effective approaches for enhancing the efficiency, reliability, and lifespan of PV systems. The outcomes of this work are expected to contribute to the optimization of solar energy generation, reduction of maintenance requirements, and development of more efficient and sustainable photovoltaic installations.

CHAPTER I

SOLAR RADIATION AND PHOTOVOLTAIC ENERGY

I.1. Introduction

Solar radiation represents the most abundant energy resource available on Earth and constitutes the fundamental source of energy for photovoltaic (PV) systems, Solar energy is harnessed through photovoltaic cells, which are capable of converting incident sunlight directly into electrical energy via the photovoltaic effect.

This chapter provides an overview of solar energy by presenting its fundamental principles, it introduces the basic concepts underlying photovoltaic systems and the mechanisms of electricity generation through the photovoltaic effect, in addition, the chapter examines the spatial and seasonal variability of solar energy and its dependence on geographical location and climatic condition.

I.2. Overview and Motivation

The growing worldwide demand for electrical energy, largely met through the consumption of fossil fuels such as oil and coal, has exerted significant pressure on finite energy resources and contributed to environmental degradation. As fossil fuels continue to dominate the global energy mix despite their limited availability, their extensive use leads to the emission of large quantities of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These emissions are recognized as major drivers of global climate change and environmental challenges (IPCC, 2007).

Moreover, the extensive reliance on fossil fuels in the transportation sector, coupled with the continuous growth of industrial activities, has significantly contributed to air pollution and intensified environmental concerns [1, 2]. In order to support sustainable economic development while preserving natural resources and ecosystems for future generations, it is essential to adopt cleaner and more sustainable energy alternatives. The successful implementation of this transition requires collective international action and cooperation, as highlighted by global initiatives and agreements such as the Kyoto Protocol [3].

In response to these challenges, renewable energy sources (RES) have been increasingly promoted as an alternative for power generation. Over the past few decades, the contribution of renewable energy to electricity grids has grown substantially due to policy measures aimed at combating climate change and ensuring a sustainable energy supply (World Energy Outlook). In 2023, RES accounted for over 33% of the global power generation capacity, as illustrated in Figure 1.1, demonstrating their rising significance in the energy mix [4]. Unlike fossil fuels, renewable energy sources such as wind, solar, biomass, and hydroelectric power produce energy without emitting greenhouse gases, thereby contributing to the mitigation of climate change and a reduction in air pollution.

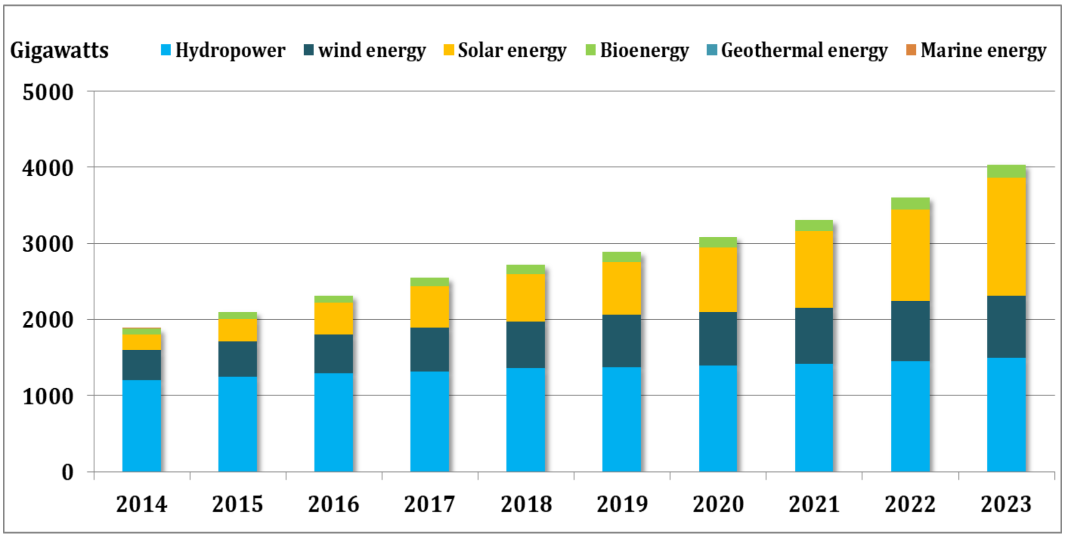


Figure I.1 Global power generating capacity [4].

Among renewable energy technologies, solar photovoltaic (PV) and wind power have witnessed remarkable growth, surpassing other renewable energy sources in terms of deployment. As illustrated in Figure 1.2, PV systems and wind energy account for approximately 33% and 28% of newly installed renewable energy capacity, respectively. This rapid expansion highlights their crucial role in supporting the transition toward a low-carbon energy future. In particular, solar energy offers significant potential for sustainable electricity generation, although its availability and effectiveness vary across different geographical regions, as shown in Figure 1.3.

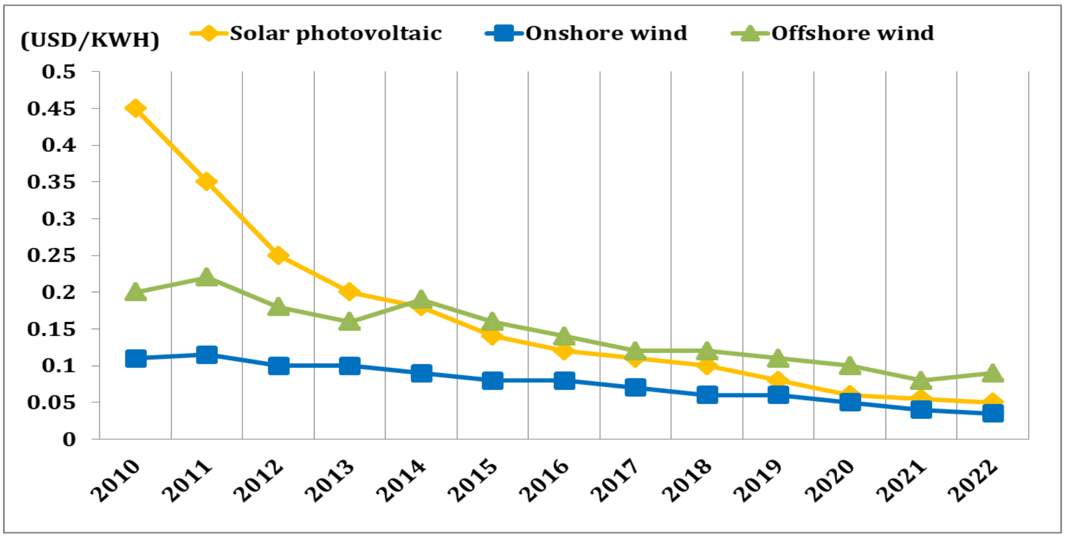


Figure I.2 Levelised cost of electricity from newly commissioned solar PV, onshore wind power and offshore wind power, 2010-2022 [5].

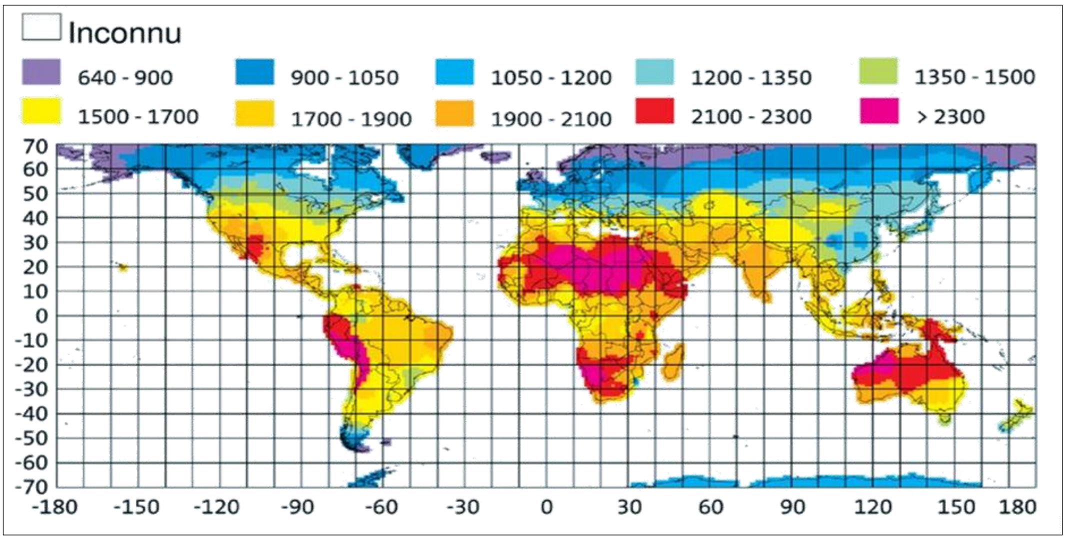


Figure I.3 Solar irradiation map of the world from photovoltaic guidenr

The levelized cost of electricity (LCOE) for renewable energy technologies has declined significantly over the past decade, enhancing their economic competitiveness. Onshore wind energy has experienced the largest cost reduction, with its global average LCOE falling by approximately 50% between 2010 and 2022, reaching USD 0.033/kWh. Solar photovoltaic (PV) technology has also achieved substantial cost improvements, recording a global average LCOE of USD 0.049/kWh in 2022. Meanwhile, offshore wind energy remains relatively more costly, with an average LCOE of USD 0.081/kWh, as illustrated in Figure 1.2.

Despite the significant improvements in cost-effectiveness, the integration of renewable energy sources, particularly solar photovoltaic (PV) systems, into electrical grids remains challenging due to their intermittent and variable nature. The direct current (DC) output generated by PV systems is highly dependent on changing environmental conditions, leading to fluctuations in voltage and power production. Consequently, direct grid integration is not feasible, necessitating the use of advanced power electronic converters (PECs) to ensure efficient energy conversion, regulation, and grid compatibility.

Power electronic converters (PECs) act as interface devices between renewable energy systems and the electrical grid. They mitigate the variability of the generated output voltage by dynamically regulating it, thereby ensuring efficient power conversion and stable power flow. Through these functions, PECs improve grid compatibility and contribute to the reliable integration and delivery of electricity generated from renewable energy sources.

I.3. Power Electronics Converters for Renewable Energy System

Power electronic converters (PECs) play a crucial role in enabling the integration of renewable energy sources (RES) into electrical grids and load systems. Their operation has a significant impact on overall system performance, particularly with respect to stability, reliability, efficiency, power quality, and energy consumption.

To ensure cost-effective and efficient energy conversion, a wide range of innovative Power Electronic Converter (PEC) systems have been developed in parallel with the growing deployment of renewable energy technologies [4]. Figure 1.4 illustrates a comprehensive framework for the integration of Renewable Energy Sources (RES) through the use of Power Electronic Converters. The integration of RES into modern electrical networks requires PEC systems to adapt the electrical output of renewable sources to the operational requirements of the power grid. As a result, considerable research efforts have been directed toward improving the performance and efficiency of PEC systems. These enhancements can generally be achieved through two main approaches: (a) the design and development of advanced power converter topologies, and (b) the implementation of sophisticated control strategies aimed at optimizing system performance and energy conversion efficiency.

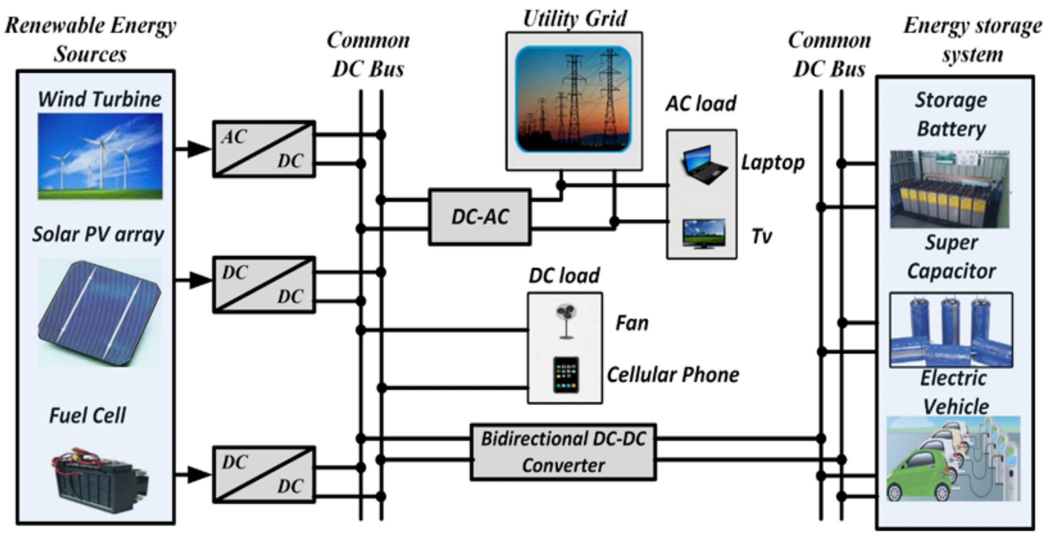


Figure I.4 Schematic exhibiting the relationship of a RES to the electricity grid.

Renewable Energy System (RES) converters are generally classified into two main categories: galvanically isolated and non-isolated converters [6], [7]. Galvanically isolated converters, commonly referred to as transformer-based converters, utilize transformers to provide electrical isolation between the input and output stages [8] [10]. Although this isolation enhances safety and operational flexibility, it also increases system cost, size, and complexity while reducing overall efficiency. In contrast, non-isolated (transformer-less) converters eliminate these drawbacks, offering a more compact, cost-effective, and efficient solution [11], [12]. Consequently, non-isolated converters are widely regarded as a preferred choice for renewable energy conversion applications.

I.3.1 Review of PV Energy System Applications

Photovoltaic (PV) energy conversion systems play a vital role in integrating renewable energy into the utility grid by enabling efficient and sustainable electricity generation. As illustrated in Figure 1.5, PV arrays convert solar irradiance into direct current (DC) power, which is regulated through a DC bus. A multilevel power electronic converter then transforms the DC power into high-quality alternating current (AC) power with low Total Harmonic Distortion (THD). A filtering stage further improves power quality and ensures compliance with grid requirements. In some configurations, a transformer is employed for voltage matching and galvanic isolation. The control system, incorporating a Maximum Power Point Tracking (MPPT) algorithm, maximizes energy extraction from the PV arrays while ensuring accurate converter operation. Finally, the generated AC power is delivered to the utility grid, enabling reliable and efficient solar energy integration.

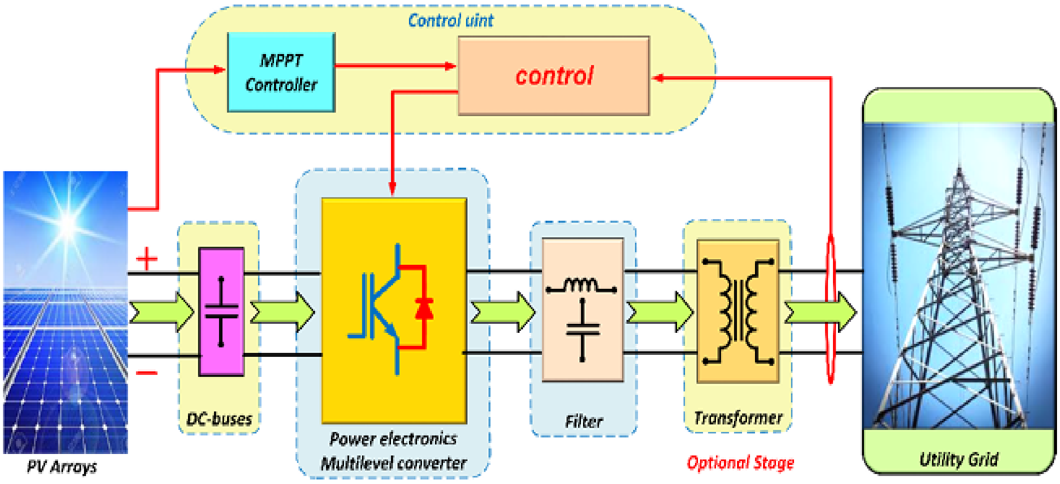


Figure I.5 A photovoltaic (PV) system with power electronics and the needed control.

I.3.2 Classification of power converters

Power electronic converters have been used in many industrial applications for efficient power conversion and energy conservation. Depending on the type of electric power conversion and the electric power flow, the power converters can be divided into the following four categories:

- AC-DC rectifiers: Convert a single-phase or three-phase AC voltage to DC is used as front-end in variable-speed motor drives and wind energy conversion systems.
- DC-DC converters: Convert a DC voltage from one level and a certain polarity to a DC voltage of another level and in some applications to another polarity.
- DC-AC inverters: Conversion from DC to variable-voltage and variable-frequency AC is used invariable-speed motor drives. Conversion of unregulated or regulated DC to fixed AC is used in grid-connection of renewable energy sources.

- AC-AC cycloconverters: Convert an AC voltage of one level, frequency and number of phases to an AC voltage of a different level, frequency, and in some applications to different number of phases.

I.3.3 Classification of DC–DC converters

Many studies have investigated various DC–DC converter topologies for renewable energy and energy storage applications with the objective of improving efficiency and addressing the limitations of conventional converters. As illustrated in Figure 2, DC–DC converters can be broadly classified into three categories according to their operating principles: linear-mode, hard-switching, and soft-switching converters [13] [15]. Linear-mode converters are characterized by their simple design, low output noise, fast dynamic response, and good voltage regulation. However, their practical application is limited by low efficiency resulting from significant power losses. In contrast, hard-switching converters offer higher efficiency and can be further classified into non-isolated and isolated topologies based on the presence of galvanic isolation. Common non-isolated hard-switching converters include buck, boost, buck–boost, and Ćuk converters, which are widely used in renewable energy systems. For grid-connected applications, isolated converters incorporating transformers are often required to ensure electrical safety and galvanic isolation. In modern microgrids, power converters, together with advanced control strategies, play a crucial role in regulating voltage levels and supplying diverse load types, including resistive, inductive, nonlinear, critical, and constant power loads (CPLs). Nevertheless, CPLs present significant control challenges, as their negative impedance characteristics can adversely affect converter stability and complicate voltage regulation when conventional control methods are employed [16], [17].

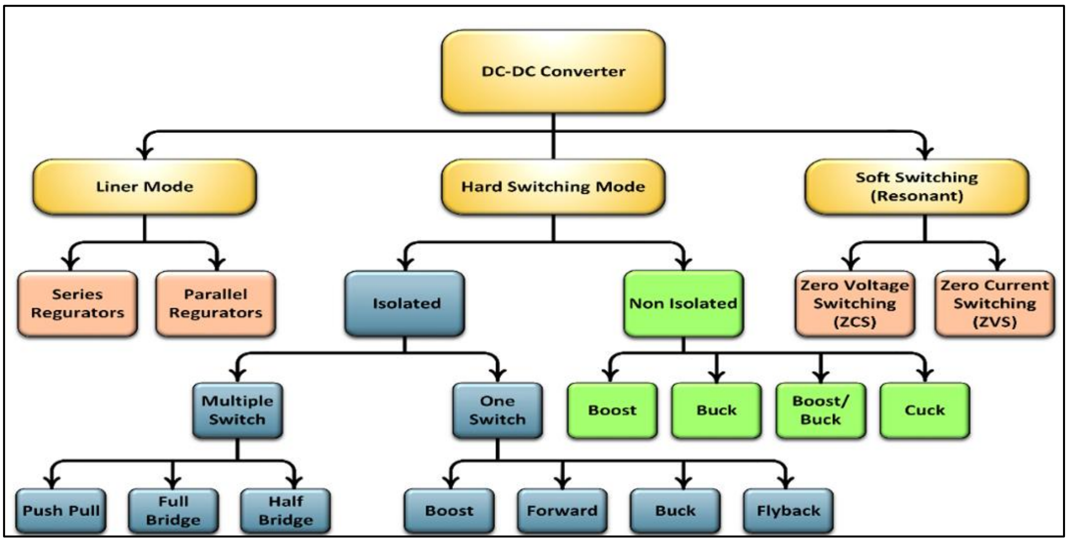


Figure I.6 Classification of DC–DC converters [18].

I.4.Solar Radiation :

Solar radiation encompasses the total spectrum of energy emitted by the Sun, in addition to high energy cosmic particles characterized by extremely high velocities, the Sun emits electromagnetic radiation spanning a wide range of wavelengths, from radio waves to gamma rays, including the visible spectrum, the solar electromagnetic emission can be accurately approximated by the radiation of a black body at an effective temperature of approximately 5800 K, in accordance with Planck’s law, the peak of the emission spectrum occurs in the visible region, particularly within the yellow wavelength range ($\lambda \approx 570$ nm), the energy distribution is nearly evenly divided between visible and infrared radiation, with approximately 1% occurring in the ultraviolet region.

As solar radiation propagates through the Earth’s atmosphere toward sea level, it undergoes multiple attenuation and filtering processes, the resulting terrestrial spectrum exhibits characteristic absorption bands primarily due to atmospheric constituents such as ozone which absorbs a substantial fraction of ultraviolet radiation as well as oxygen, carbon dioxide, and water vapor [1].

Figure I.7: Representation of Solar Radiation

I.4.1.Radiation Spectrum:

Solar energy, although often perceived as an abstract concept, corresponds in practical terms to the heat and light emitted by the Sun, The development of photovoltaic technology during the twentieth century enabled the direct utilization of this energy source for electricity generation , through the use of photovoltaic cells assembled in solar panels, incident solar radiation is converted into electrical energy by means of the photovoltaic effect, thereby providing a sustainable and reliable source of power for modern technological applications.

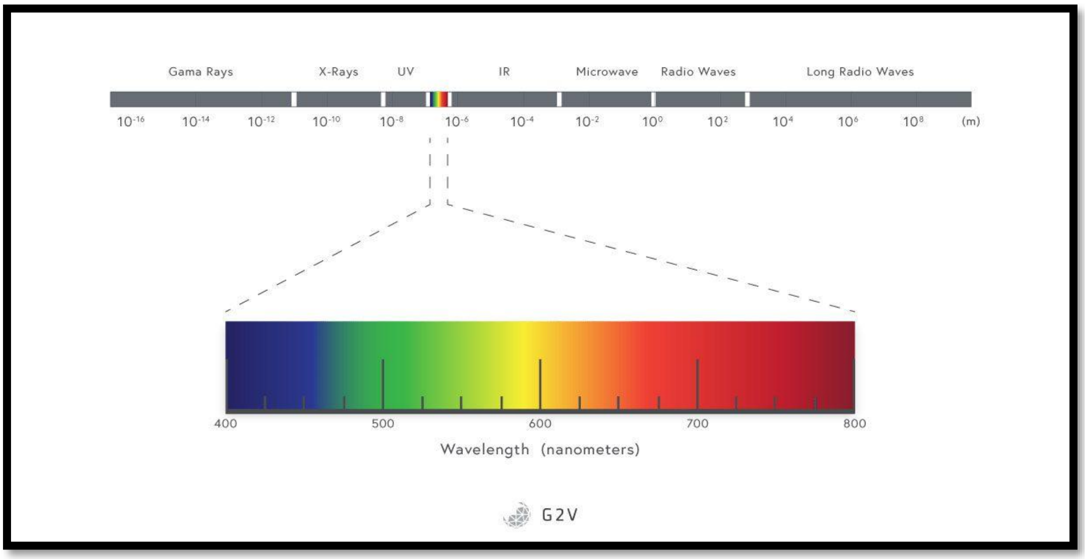


Figure I.8: Solar Radiation Spectrum

Despite the broad extent of the electromagnetic spectrum, approximately 99.8% of the Sun's radiant energy is emitted within a relatively narrow wavelength range extending from about 20 nm to 2500 nm, However, only a limited portion of this solar radiation reaches the Earth's surface, the transmitted spectrum includes radio waves with wavelengths on the order of several decameters up to the soft ultraviolet region, whereas the remaining fraction is either reflected back into space or absorbed by the Earth's atmosphere and ionosphere [2].

Figure (1.3) presents the solar radiation spectrum, the spectral composition of solar energy is distributed approximately as follows: 5% in the ultraviolet region, 42% in the visible range, and 53% in the near infrared region.

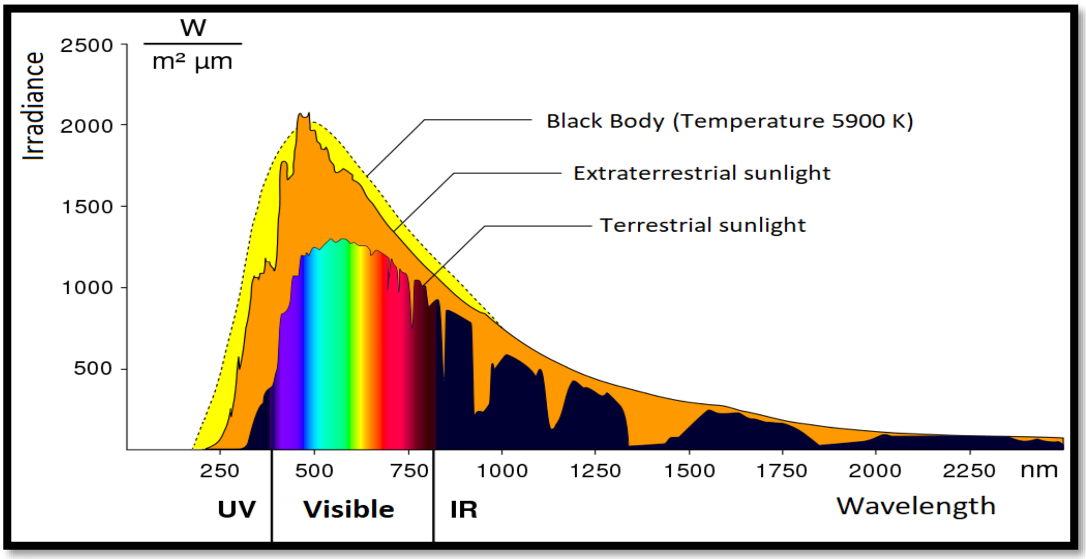


Figure I.9: Representation of Solar Radiation Spectrum

I.5.Conversion of Solar Radiation by PV Effect:

A photovoltaic (PV) cell is composed of two silicon layers that are deliberately doped to form regions of opposite electrical polarity, the p type layer is created by introducing acceptor impurities, such as boron atoms, which result in a predominance of positive charge carriers (holes), whereas the n type layer is formed by incorporating donor impurities, such as phosphorus atoms, leading to an excess of free electrons, the junction between these two regions establishes an internal electric field, known as the potential barrier, when a photon with sufficient energy is absorbed by the semiconductor material, it excites an electron from the valence band to the conduction band, thereby generating an electron hole pair, this phenomenon, referred to as the photovoltaic effect, produces a potential difference across the p n junction, when an external circuit is connected, charge carriers are driven by the internal electric field, resulting in the flow of electrons and the generation of an electric current [1].

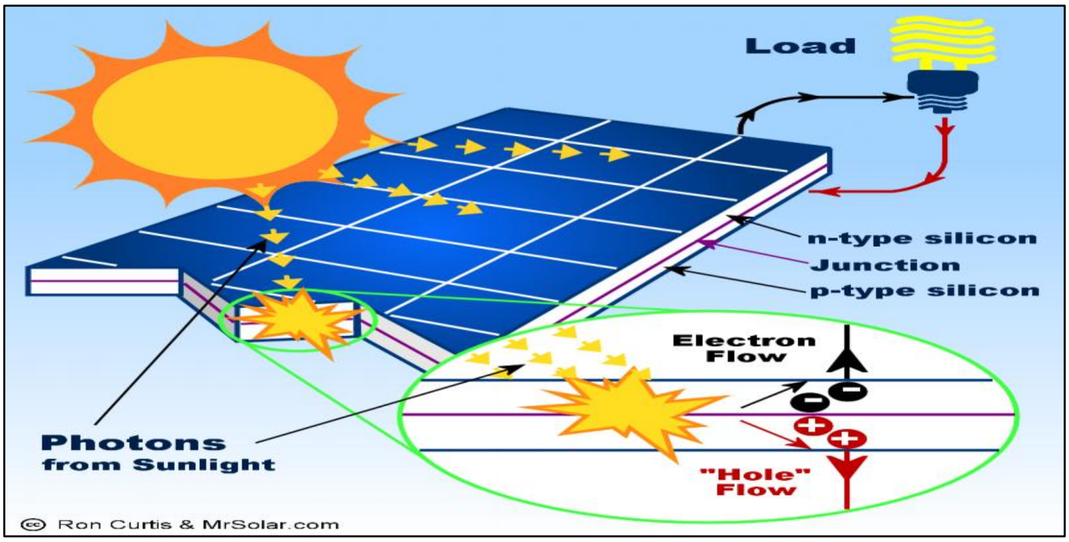


Figure I.10: Solar Radiation Conversion by PV Effect

I.6.Photovoltaic Generator:

A photovoltaic generator is characterized by its electrical behavior, particularly by the current voltage (I=f(V)), relationship, as depicted in Figure (1.5)..

This model is widely employed to predict the electrical output of the photovoltaic device, namely the voltage and current, as a function of two primary operating parameters: the cell temperature and the incident solar irradiance.

For a given operating voltage, the current generated by a photovoltaic module is governed primarily by the level of illumination and the temperature of the cell, Under constant irradiance and temperature conditions, the conversion efficiency of a solar cell depends on the electrical load connected to the system, in the limiting cases of open circuit operation ($Rc = \infty$, $I = 0$, $V = Voc$) and short circuit operation ($Rc = 0$, $I = Icc$, $V = 0$), no electrical power is delivered to the external circuit, between these two extremes, an optimal load resistance Ropt exists, at which the photovoltaic cell delivers maximum power, defined as(P=Vmax × Imax) corresponding to the maximum power point (Pmax) [2]

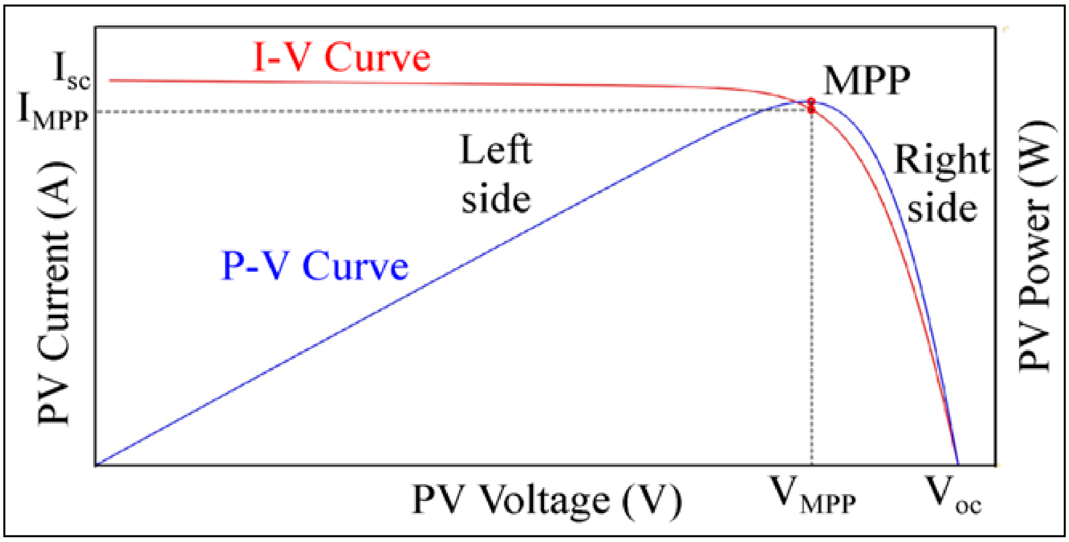


Figure I.11: Typical Characteristics of a PV Generator

The energy efficiency of the solar cell is defined as $\eta = P/P\gamma$, where $P\gamma$ is the incident light power on the surface of the cell, for the optimal value Ropt of the load resistance Rc, the efficiency of the solar cell is maximum, and ηmax=Pmax/$P\gamma$, the value of Ropt is not a characteristic constant for a given cell, but depends on the spectrum of the incident radiation and the junction temperature, in fact, the efficiency decreases as the temperature increases, which sometimes leads to the construction of hybrid sensors resulting from the combination of a thermal sensor and a solar cell. These sensors allow the simultaneous production of hot water and increase the photovoltaic efficiency by cooling the cell.

The power provided by the solar cell ($P=I\times V$) and its efficiency depend on the material used and the manufacturing technology (amorphous silicon, polycrystalline silicon, monocrystalline silicon), the junction geometry (layer thickness, multilayers, etc.), and external parameters (temperature, spectrum and power of the incident radiation, external electrical circuit connected to the cell, etc.).

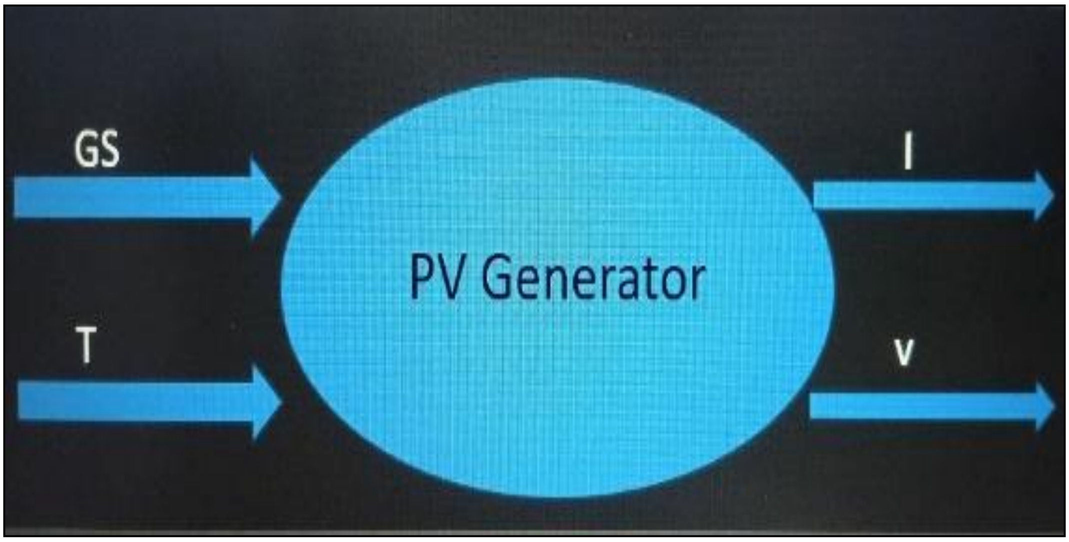


Figure I.12: Block Diagram of a PV Generator

I.6.1.Photovoltaic Cell:

Photovoltaic modules are composed of an array of interconnected solar cells, these cells are typically encapsulated in a resin and sandwiched between two layers of tempered glass in double glass modules, or between a glass layer and a Tedlar sheet in glass/Tedlar modules, the assembly is commonly housed within an anodized aluminum frame; however, frameless designs are also available for building integrated applications, often supported by aluminum profiles on façades or rooftops.

The electrical power output of a module is determined by its surface area and the incident solar irradiance, expressed in peak watts (Wp), which represents the maximum achievable power under standard reference conditions (1,000 W/m²), the voltage generated by a module depends on the number of cells connected in series, Low power modules, typically below 75 Wp, generally operate at voltages ranging from 12 to 15 volts, Modules with higher power ratings are produced by increasing the number of series connected cells to raise the voltage, and by increasing the number of parallel cell strings to enhance the current.

Consequently, operating voltages of 24 volts or higher can be achieved, depending on the configuration of the system being supplied.

Module surface areas vary according to manufacturer specifications, generally ranging from 0.5 to 1 m², but may reach up to 3 m² for special orders or large scale production, multiple interconnected modules form a panel, and a collection of interconnected panels constitutes a photovoltaic array, by arranging modules in series and/or parallel, a wide range of voltage and power outputs can be obtained, enabling flexibility in system design and application [1].

I.6.2.Modelling of a PV Cell:

The operation of a photovoltaic module is commonly described using the standard single diode model, which was originally developed by Shockley to represent an individual photovoltaic cell and subsequently extended to photovoltaic modules by modeling them as an assembly of identical cells connected in series and/or in parallel. In the scientific literature, a photovoltaic cell is generally represented as an electrical current generator whose behavior is equivalent to that of a current source connected in parallel with a diode, to account for the physical phenomena occurring at the cell level, the model is augmented by two resistive elements: the series resistance Rs and shunt resistance Rsh, as depicted in the equivalent circuit shown in Figure (1.7).

The series resistance characterizes the internal resistive losses of the cell and is mainly influenced by the resistivity of the semiconductor material, the contact resistance of the current collecting grids, and the intrinsic resistivity of these grids, the shunt resistance, on the other hand, represents leakage currents across the junction and depends primarily on the manufacturing quality and fabrication process of the cell.

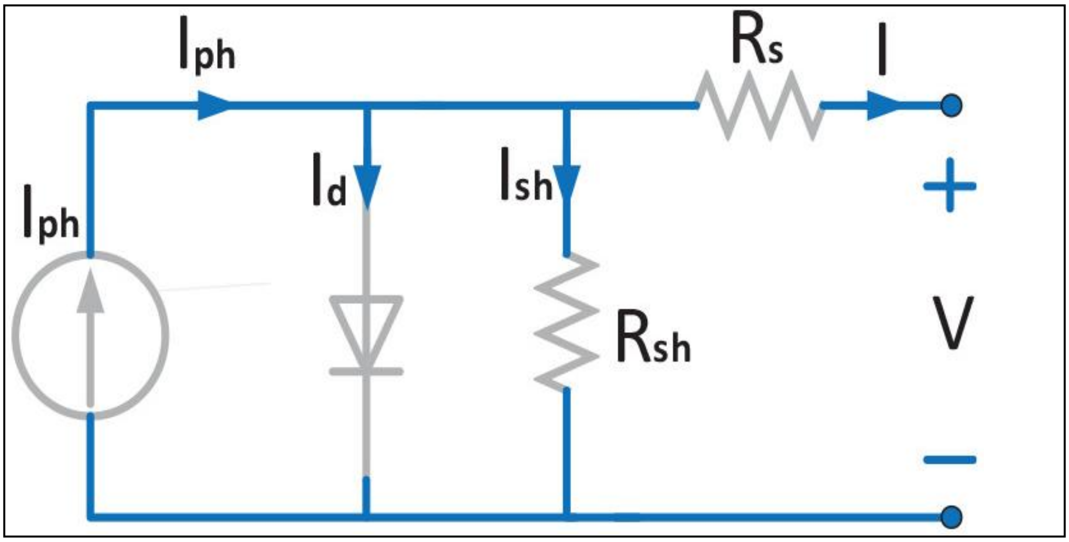


Figure I.13: Equivalent Circuit of a PV Cell

I.6.3.Types of Photovoltaic Cells :

Photovoltaic solar panels are made up of photovoltaic cells and vary according to type:

1.Monocrystalline Cells: Monocrystalline silicon is produced through the controlled cooling of molten silicon, upon solidification, the material forms a single, uniform crystal, which is subsequently sliced into thin wafers to fabricate photovoltaic cells, this material is characterized by a uniform blue coloration, free from visible crystal boundaries or impurities, reflecting its high degree of structural purity and crystallographic uniformity**.**

Figure I.14: Monocrystalline Cells

2.Polycrystalline Cells: Polycrystalline silicon is produced by melting silicon in a square or rectangular metal mold, known as an ingot, upon solidification, the material forms multiple crystals, resulting in a blue colored surface with a distinctive speckled pattern caused by the grain boundaries, this characteristic texture not only differentiates polycrystalline cells visually from monocrystalline cells but also reflects the presence of multiple crystallites within the material, which can influence its electrical and optical properties.

Figure I.15: Polycrystalline Cells

3. Hydrogenated Amorphous Cells: Amorphous silicon is obtained from silicon gas, This gas is vaporized onto a support, either glass, flexible plastic, or metal, using a vacuum deposition process, these PV cells are dark gray.

Figure I.16: Hydrogenated Amorphous

I.6.4.The Impact of Temperature on Solar Panel:

Temperature has a significant impact on the performance of solar panels, here's how:

- **Reduction in Efficiency:** The efficiency of solar panels decreases with increasing temperature, as higher temperatures reduce the effectiveness of converting sunlight into electrical energy.
- **Voltage Decrease:** The output voltage of a solar panel decreases with increasing temperature, this occurs because the semiconductor material becomes less effective at charge transport at elevated temperatures, reducing the panel's electrical potential**.**
- **Power Output Reduction:** Elevated temperatures can reduce the power output of solar panels, as the concurrent decreases in voltage and conversion efficiency directly diminish the overall electrical power generated.
- **Thermal Degradation:** Prolonged exposure to high temperatures can lead to thermal degradation of solar panel materials, resulting in a gradual decline in both efficiency and operational lifespan.
- **Operating Temperature Range:** Solar panels are engineered to function optimally within a specified temperature range. Exceeding this range can further compromise their performance, although solar panels continue to generate electricity at elevated temperatures, their efficiency declines as the operating temperature rises, negatively affecting overall energy output.

I.7.Advantages and Disadvantages of PV Energy:

I.7.1. Advantages:

- **Renewable Energy:** Solar energy constitutes an abundant and widely accessible renewable resource globally, rendering it a sustainable long term energy source.
- **Low Greenhouse Gas Emissions:** Solar energy generates no greenhouse gases during operation, thereby contributing to the reduction of carbon emissions and aiding in the mitigation of climate change.
- **Decreasing Costs:** Solar technologies have experienced a substantial reduction in costs over the years, rendering solar energy increasingly competitive relative to conventional energy sources.
- **Energy Independence:** Photovoltaic systems enable users to generate their own electricity, thereby reducing reliance on energy providers and vulnerability to market price fluctuations.
- **Low Maintenance:** Solar installations demand minimal maintenance once deployed, thereby reducing long term maintenance costs.

I.7.2. Disadvantages:

- **Sunlight Variability**: Solar energy generation is contingent upon the availability of sunlight, rendering photovoltaic electricity production variable and intermittent, this often necessitates the implementation of energy storage systems or integration with other energy sources to ensure a stable power supply.
- **High Initial Costs:** Despite the declining costs of solar technologies, the upfront capital required for solar installations remains relatively substantial.
- **Environmental Impact:** Although solar energy is widely regarded as a clean energy source, the production and end of life disposal of solar panels can exert environmental impacts.
- **Space Requirement**: Solar installations typically necessitate extensive land or rooftop areas to accommodate photovoltaic panels, which can present significant challenges in densely populated urban environments or regions with limited available space.
- **Dependency on Weather Conditions:** Solar installations typically necessitate extensive land or rooftop areas to accommodate photovoltaic panels, which can present significant challenges in densely populated urban environments or regions with limited available space.

I.8.Conclusion:

In summary, this chapter provided a comprehensive overview of solar radiation and the principles of photovoltaic energy conversion, the mechanisms by which solar cells exploit the photovoltaic effect to produce electricity from sunlight were examined, the modeling approaches and performance characteristics of photovoltaic generators were analyzed, including the key factors affecting their efficiency, such as temperature and load resistance, various types of photovoltaic cells, categorized according to silicon crystal structure, were presented.

Additionally, the chapter reviewed the components of photovoltaic modules and outlined the principal advantages and limitations associated with solar photovoltaic technology.

CHAPTER II

Modeling and control of photovoltaic systems integrated into the electrical grid

II.1. Introduction

As the global demand for renewable energy continues to rise, photovoltaic (PV) systems have emerged as a vital pillar for sustainable electricity generation.

Nevertheless, the successful integration of these systems into the power grid hinges on sophisticated modeling, advanced control strategies, and efficient power conversion methods to guarantee operational reliability and high performance.

This chapter investigates the core elements of grid-tied PV systems, emphasizing essential components such as DC-DC converters, Maximum Power Point Tracking (MPPT), Voltage Source Inverters (VSI), and grid synchronization protocols, Each component is fundamental to optimizing energy conversion processes and upholding power quality standards.

The chapter begins with an overview of PV system modeling, followed by an examination of DC-DC converters and their significance in voltage regulation, Subsequent sections delve into MPPT algorithms designed to maximize energy harvesting from solar arrays, The focus then shifts to VSI units and their control mechanisms, which are indispensable for converting DC power to AC and ensuring stable grid integration.

Finally, various grid synchronization techniques are discussed to ensure seamless and reliable operation.

II.2. Architecture of a photovoltaic module.

II.2.1.Grouping cells in series

An elementary photovoltaic cell constitutes a low-power electrical generator, insufficient on its own for most domestic or industrial applications. Photovoltaic generators are, therefore, made by connecting a large number of elementary cells in series and/or parallel.

A series connection of (Ns) cells increases the voltage of the photovoltaic generator. The cells are traversed by the same current, and the resulting characteristic of the series connection is obtained by adding the voltages of the individual cells, as represented in Figure II.1.

Equation (1.3) summarizes the electrical characteristics of a series connection of (Ns) cells:

$$V_{oc_{NS}} = N_S \times V_{oc};\ I_{cc_{NS}} = I_{cc} \qquad \text{II.1}$$

$V_{oc_{Ns}}$: The sum of the open-circuit voltages of the (Ns) cells in series.

$I_{cc_{Ns}}$: The short-circuit current of the (Ns) cells in series.

This connection system is generally the most commonly used for commercial photovoltaic modules.

While technological strides have enabled a steady increase in a cell's current output by expanding its surface area, the individual voltage remains inherently low, Consequently, series connection is employed to scale up the cumulative voltage, thereby maximizing the total power output.

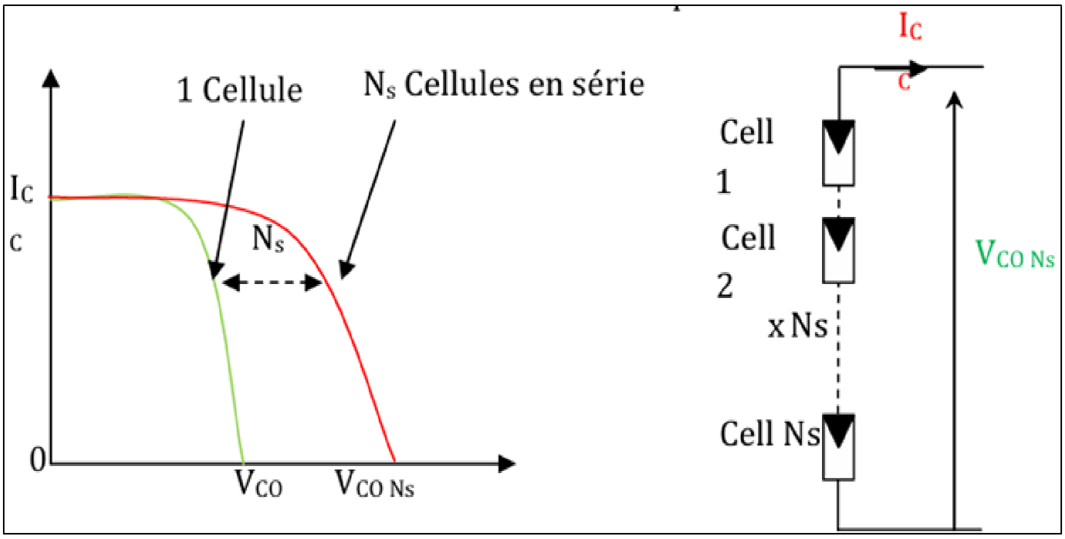


Figure II.1: Resulting characteristic of a series connection of ($\boldsymbol{Ns}$) cells.

II.2.2. Parallel Connection of Cells

A parallel connection of (Np) cells is possible and allows for an increase in the output current of the generator thus created. In a grouping of identical cells connected in parallel, the cells are subjected to the same voltage, and the resulting characteristic of the grouping is obtained by adding the currents.

Figure II.2 summarize the electrical characteristics of a parallel connection of (Np) cells.

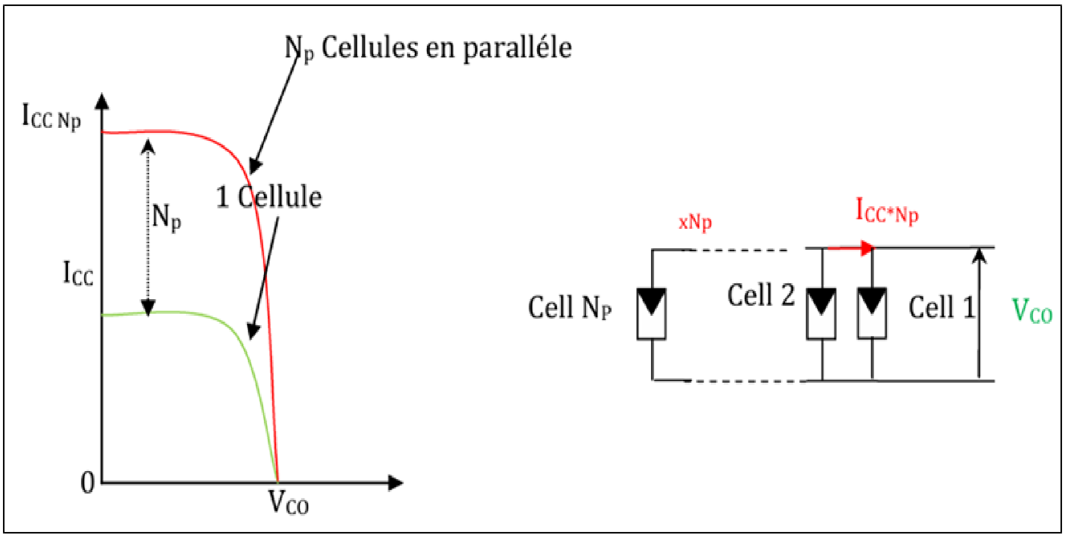


Figure II.2: Resulting characteristic of a parallel connection of ($\boldsymbol{Np}$) cells [41].

$$I_{ccNp} = N_p \times I_{cc} \quad \text{II.2}$$

$$V_{ocNp} = V_{oc} \quad \text{II.3}$$

I_{ccNp}: The sum of the short-circuit currents of (Np) cells connected in parallel.

V_{ocNp}: The open-circuit voltage of (Np) cells connected in parallel.

II.2.3.Hybrid Connection of Cells (Series & Parallel)

Depending on the series and/or parallel connection of these cells, the values of the total short-circuit current and the total open-circuit voltages are given by the following relations:

$$I^{t}{}_{cc} = N_p \times I_{cc} \quad \text{II.4}$$

$$V_{toc} = N_c \times V_{oc} \quad \text{II.5}$$

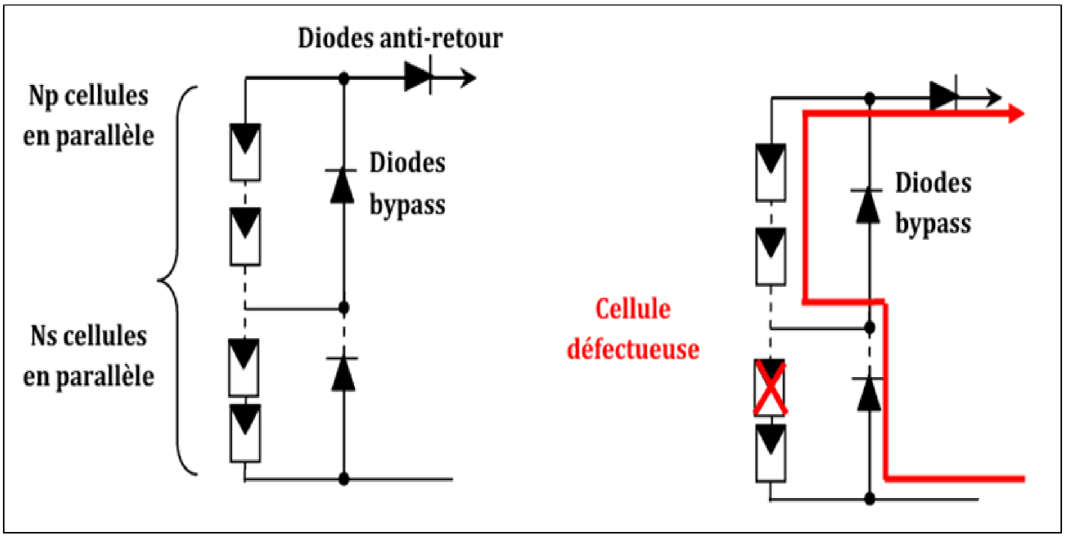


Figure II.3: Resulting characteristics of a hybrid connection of (***Ns x Np***) cells [41] .

Where:

N_c: Number of cells connected in parallel.

N_p: Number of cells connected in series.

$I^{t}{}_{cc}$: Total short-circuits current.

$V^{t}{}_{oc}$: Total open-circuit voltage.

A photovoltaic (PV) generator's I-V characteristics are essentially the cumulative result of its Ns×Np cell configuration, This performance is highly sensitive to environmental and physical factors such as irradiance levels, operating temperatures, cell degradation, and partial shading.

Notably, even a single compromised cell within a series string can drastically bottleneck the entire module's current output.

If the load demand exceeds the current generated by a shaded cell, that cell transitions into a 'receiver' mode with negative voltage, leading to excessive power dissipation, This risk of thermal damage is termed the 'Hot Spot' phenomenon, To mitigate this, bypass diodes are integrated to isolate underperforming segments. While this protective measure prevents cell destruction by rerouting current, it inevitably results in a 'voltage drop' and a reduction in total power output, as the entire string associated with the active diode becomes electrically redundant.

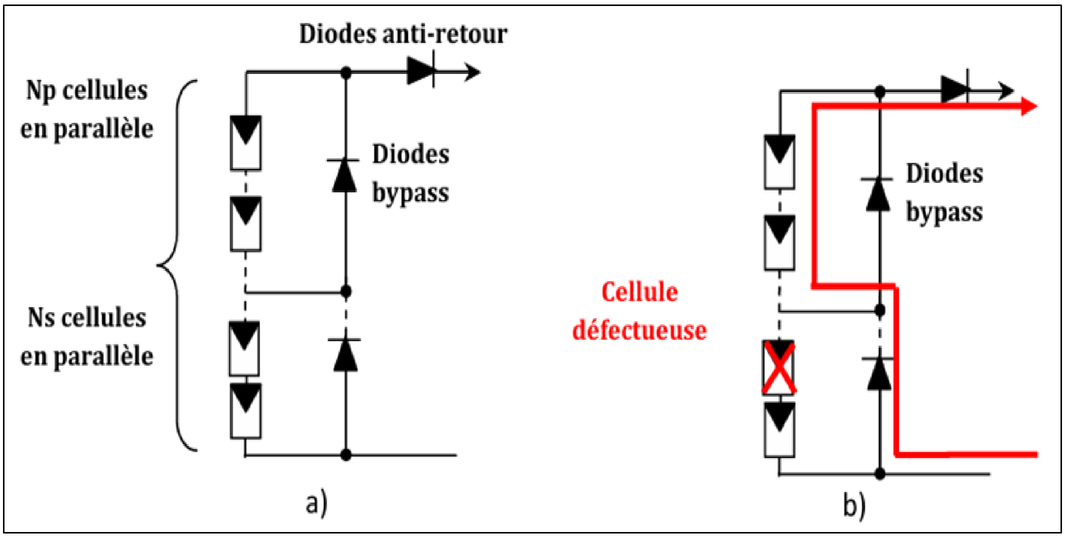


Figure II.4: a) Classical architecture of a photovoltaic module with protective diodes.
b) Failure of one of the PV module cells and activation of the bypass diode, highlighting the circulation current .

This phenomenon of partial power loss should be compared to the total loss of a module in the event of a problem with a single cell in a module operating without protections.

II.3.Modeling of Photovoltaic Installation Elements

II.3.1.Conversion of Light into Electricity

The photovoltaic generator converts light into electrical energy using semiconductor devices, commonly referred to as "photovoltaic cells," which are typically made from semiconductor materials, usually silicon [42].

The photovoltaic generator, or "solar field," consists of photovoltaic panels interconnected in series (Nps) and/or in parallel (Npp) to produce the required power. These panels are mounted on a metallic frame that supports the solar field at a specific tilt angle.

The photovoltaic panel itself is made up of (Ncs) cells in series and (Ncp) cells in parallel, encapsulated under glass. Series connections of multiple cells increase the voltage for a given current, while parallel connections increase the current while maintaining the voltage.

II.3.2.Single-Diode Model

The characteristic (I-V) of an elementary cell is modeled by the equivalent circuit represented in Figure II.5. This circuit includes a current source and a diode in parallel, as well as series resistance (Rs) and parallel (shunt) resistance (Rsh), to account for dissipative phenomena at the cell level [43.44].

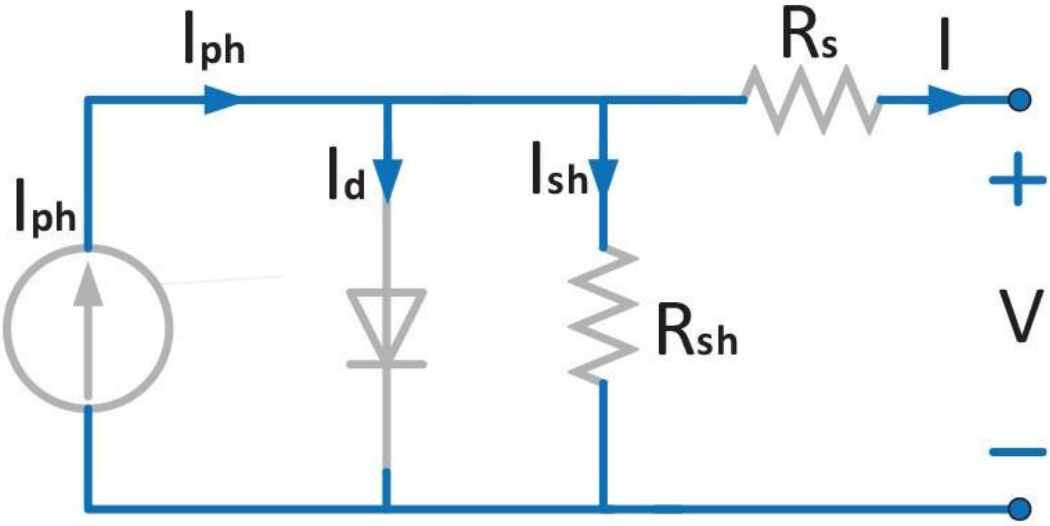


Figure II.5: Equivalent electrical schematic of the PV cell with a single diode.

With:

I : Current delivered by the cell.

I_{ph} : Photocurrent generated by the cell (proportional to the incident radiation)

Id : Current of the diode.

I_{sh} : Shunt current.

$$I_{ph} = P_1 \cdot E_G \cdot \left[1 + P_2 \cdot (E_G - E_{\text{ref}}) + P_3 \cdot (T_j - T_{\text{jref}})\right] \quad \text{II.6}$$

$$T_j = T_a + E_G\left(\frac{N_{oct} - 20}{800}\right) \quad \text{II.7}$$

$$I_d = I_s\left[\exp\left(\frac{q}{A \cdot K \cdot T_j}(V_c R_{s-p} \cdot I_c)\right) - 1\right] \quad \text{II.8}$$

$$I_s = P_4 \cdot T_j^3 \exp\left(\frac{-E_G}{K \cdot T_j}\right) \quad \text{II.9}$$

$$I_{sh} = \frac{V_c}{R_{sh}} \quad \text{II.10}$$

$$I_c = I_{ph} - I_d - I_{sh} \quad \text{II.11}$$

With:

EG: Solar irradiation.

$P1$, $P2$, $P3$, $P4$: Constants dependent on the nature of the cell material, determined experimentally by the manufacturer.

Ta: Ambient temperature.

$Tref$: Reference temperature (298 K).

Tj: Temperature of the cell.

$Noct$: Nominal operating temperature of the solar cell, as provided by the manufacturer (45°C).

Eef: Reference illumination (1000 W/m²).

Is: Saturation current of the diode.

Eg: Energy gap for crystalline silicon (1.12 eV).

A: Ideal factor of the junction ($1 < A < 3$).

R_{sp}: Series resistance of a photovoltaic panel.

R_{sh-p}: Equivalent resistance of a photovoltaic panel.

q: Electron charge (1.6×10^{-19} C).

K: Boltzmann constant (1.38×10^{-23} J/K).

Vc: Voltage across the cell terminals.

II.3.3.Two-Diode Model

The two-diode model includes an additional diode for better curve fitting. This diode represents the phenomenon of recombination of minority carriers, both on the surface of the material and within its volume.

This model appears more sophisticated and provides greater precision but is somewhat complex and challenging to solve. It requires knowledge of four parameters under standard sunlight and temperature conditions. These parameters are generally provided by the manufacturer or can be obtained through module testing fewer than three conditions: shortcircuit current (Icc), open-circuit voltage (Voc), maximum voltage ($Vmax$), and maximum current ($Imax$) at the point of maximum power.

Temperature coefficients are also necessary in this modeling technique to account for the effect of temperature on the critical parameters of the solar cell.

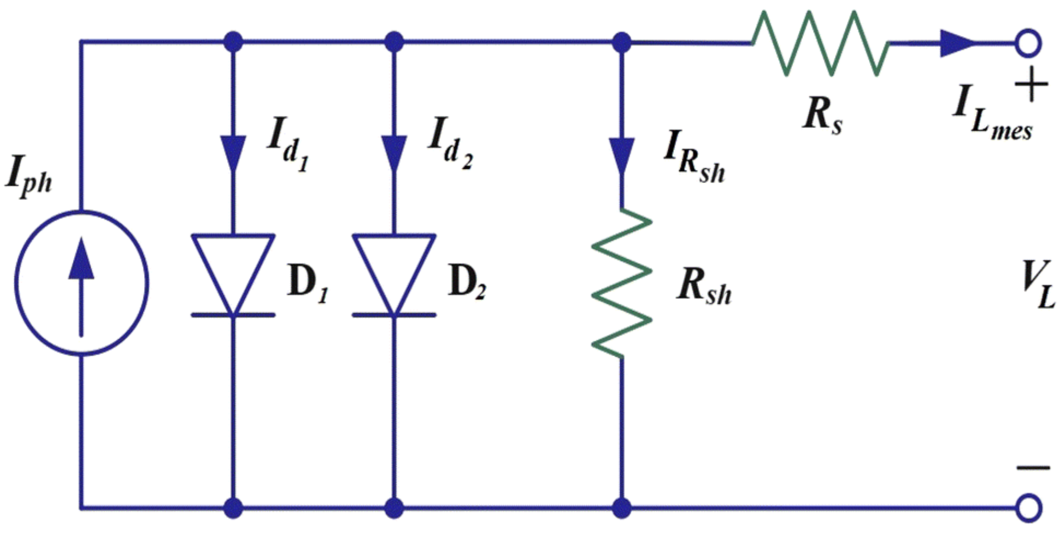


Figure II.6: Electrical two-diode equivalent model of a photovoltaic cell.

$$I_{d1} = I_{s1}\left[e^{\frac{q(V+IR_S)}{n_1 kT}} - 1\right] \qquad \text{II.12}$$

with :

$$I_{d2} = I_{s2}\left[e^{\frac{q(V+IR_S)}{n_2kT}} - 1\right] \quad \text{II.13}$$

So:

$$I_{ph} = I + I_{d1} + I_{d2} + I_{Rp} \quad \text{II.14}$$

$$I = I_{ph} - I_{d1} - I_{d2} - I_{Rp}$$

So:

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_S)}{n_1kT}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_S)}{n_2kT}} - 1\right] - \frac{V+IR_s}{R_p} \quad \text{II.15}$$

$n1$, $n2$: Ideality factors of diodes $d1$ and $d2$ (ranging between 1 and 2, depending on the technology).

The photocurrent depends on the temperature, and its expression is:

$$I_{ph}(T) = I_{ph}(T = 298K)[1 + (T - 298K) \cdot (5 \cdot 10^{-4})]$$

I_{s1}, I_{s2}: These are the saturation currents of diodes $d1$ and $d2$, respectively, and they depend on the temperature:

$$I_{S1} = K_1T^3e^{\frac{-Eg}{KT}}$$

$$I_{S2} = K_2T^{\frac{5}{2}}e^{\frac{-Eg}{KT}} \quad \text{II.16}$$

Where:

Eg: Energy, with

K1=1.2A/cm2 T3K1 and K2=2.9×105A/cm2 T5/2.

For a solar panel consisting of z cells connected in series, and considering the model in Figure II.6, the equation describing this panel is:

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IzR_S)}{zn_1kT}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IzR_S)}{nz_2kT}} - 1\right] - \frac{V+IzR_S}{R_p} \quad \text{II.17}$$

The Three-Diode Model: The third diode is included in the equivalent schematic to account for effects not considered in the other models (e.g., leakage current related to the diodes).

The current and voltage across the terminals of a photovoltaic panel are given by:

$$I_P = N_{cp}I_c \quad \text{II.18}$$

$$V_P = N_{cs}V_c$$

Whereas the current and voltage across the terminals of a photovoltaic generator are given by:

$$I_g = I_{Pv} = N_{pp}I_P = N_{pp}N_{cp}I_c \quad \text{II.19}$$

$$V_g = V_{Pv} = N_{ps}V_P = N_{ps}N_{cs}V_c$$

The current generated by the photovoltaic generator at a given voltage depends solely on the illumination and the temperature of the cell.

I. Simulation results

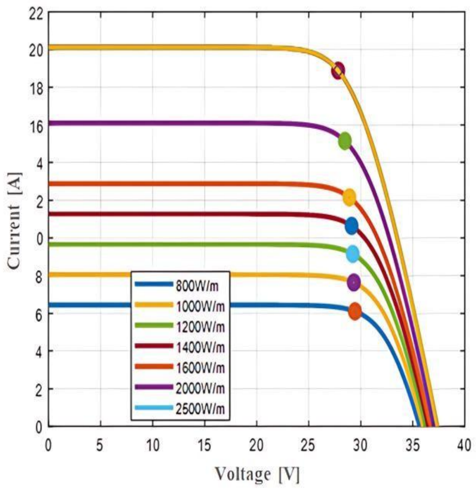


Figure II.7: I-V characteristics, variation of of irradiance at constant temperature

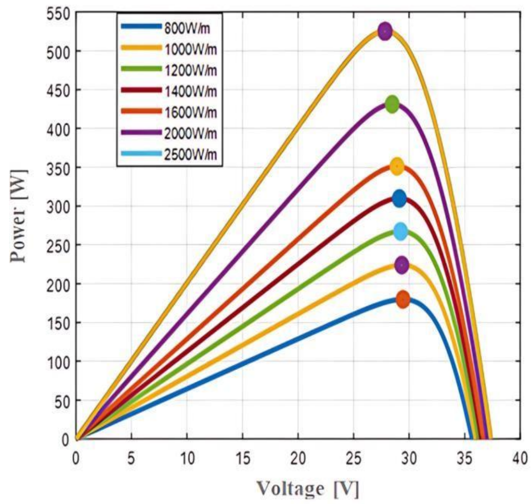


Figure II.8: P-V characteristics, variation irradiance at constant temperature.

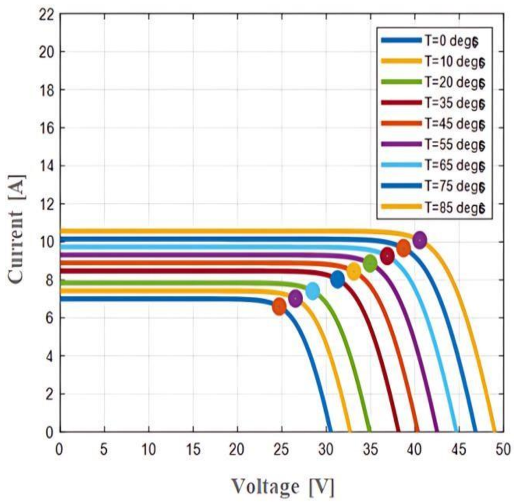


Figure II.9: I-V characteristics, temperature variation at constant solar radiation

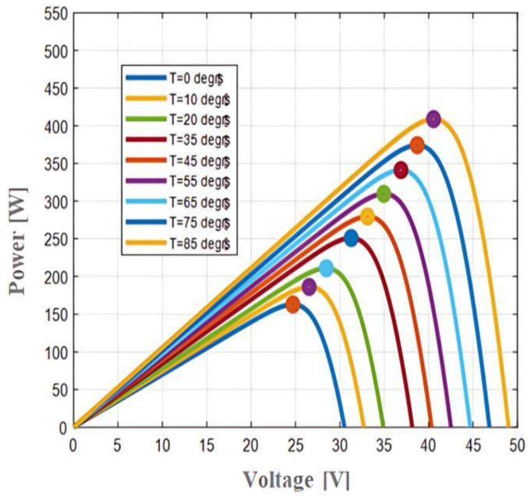


Figure II.10: P-V characteristics, temperature variation at constant solar radiation

The behavior of a photovoltaic (PV) module is highly influenced by variations in irradiance (G) and temperature (T) due to their significant impact on the module's power output. Figure II.7 depicts the variations in current (I_{pv}) and voltage (v_{pv}) with respect to voltage for different illumination levels, while maintaining a constant temperature of 25°C. Multiple P (V) curves are shown, representing the maximum power points (v_{mp},I_{mp}). According to Figure II.8, the open circuit voltage and short circuit current vary proportionally to the illumination. In

Figure II.9, with constant illumination ($1000 w/m^2$) and increasing temperature, the open circuit voltage (v_{oc}) decreases while the short circuit current (I_{sc}) remains relatively stable. Therefore, the operation of a PV module is primarily dependent on the surrounding environmental conditions. It is crucial to consider these factors when sizing a PV system to achieve the desired power output.

The impact of irradiance on a solar PV module is illustrated by the I-V and P-V characteristic curves in Figure II.7 and Figure II.8, where the irradiance intensity ranges from $100\ w/m^2$ to $1000\ w/m^2$at a fixed temperature of 25°C. The current remains constant as voltage increases up to 30 V, after which it starts to decrease. Additionally, the current increases with higher irradiance intensity, demonstrating the significant effect of irradiance on the short circuit current. Conversely, the open circuit voltage shows minimal change. The proof of maximum power can be found in the power performance curves.

Observing the figure, when the temperature varies from 0 to 80°C, it is evident that increasing temperature leads to a decrease in power (W) with voltage variations (V).

II.4.factors and phenomena affecting the efficiency of photovoltaic cells

II.4.1.Dust

The two figures represent curves illustrating the effect of environmental factors on the performance of photovoltaic systems. Figure A shows the relationship between voltage (V) and power under the influence of an environmental factor such as humidity. Power gradually increases with voltage until it peaks at approximately 13 V and 45 W, a point known as the maximum power point (MPP). Power then declines sharply, indicating a decline in system efficiency. This may be attributed to the effect of humidity on the conductive properties or overall performance of components. Figure B shows the relationship between current and voltage for a photovoltaic system under the influence of dust. The current remains nearly constant up to a certain voltage, reflecting the optimal operating area. It then begins to gradually decrease, followed by a sharp drop after reaching the maximum voltage, indicating a clear negative effect of dust. This behavior reflects partial shading or irregular scattering of light resulting from dust accumulation, leading to a decline in electrical energy production and conversion efficiency. In this context, regular maintenance and cleaning are recommended to improve the efficiency of the photovoltaic system.

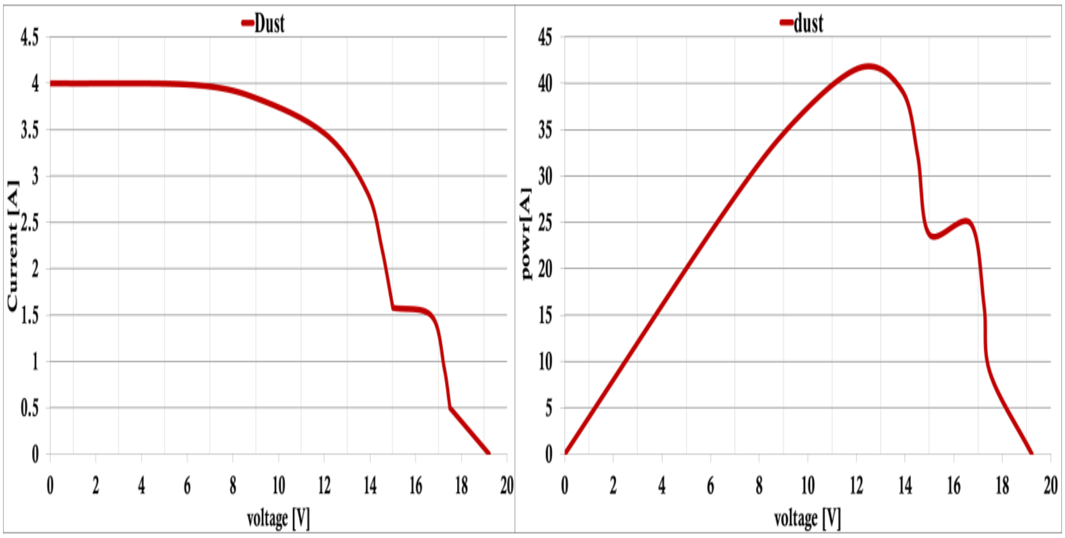


Figure 11: The impact of dust accumulation on the PV panels. I-V curves below radiation levels show a reduction in current output and obvious distortion, emphasizing the importance of regular maintenance and repair

II.4.2.Shadow

The two figures represent curves illustrating the effect of partial shading on the performance of photovoltaic systems. Figure A shows the relationship between electrical power and voltage under partial shade. The behavior is nonlinear and exhibits multiple peaks, reflecting the varying efficiency of solar cells due to some being shaded while others remain in optimal operation. These multiple peaks indicate the presence of multiple maximum power operating points (MPPs), making the maximum power point tracking (MPPT) process more complex and increasing the likelihood of the system reaching suboptimal power points. Figure B shows the current-voltage relationship for a solar cell under the same effect. The current starts constant at low voltage and gradually decreases as the voltage increases, with clear breaks in the curve due to the effect of the shade on the cells. Different current levels reveal the presence of multiple operating points, calling for the use of advanced technologies such as multi-point MPPT or bypass diodes to improve performance. Partial shading is an environmental factor that negatively impacts system efficiency, requiring effective engineering solutions to mitigate its impact.

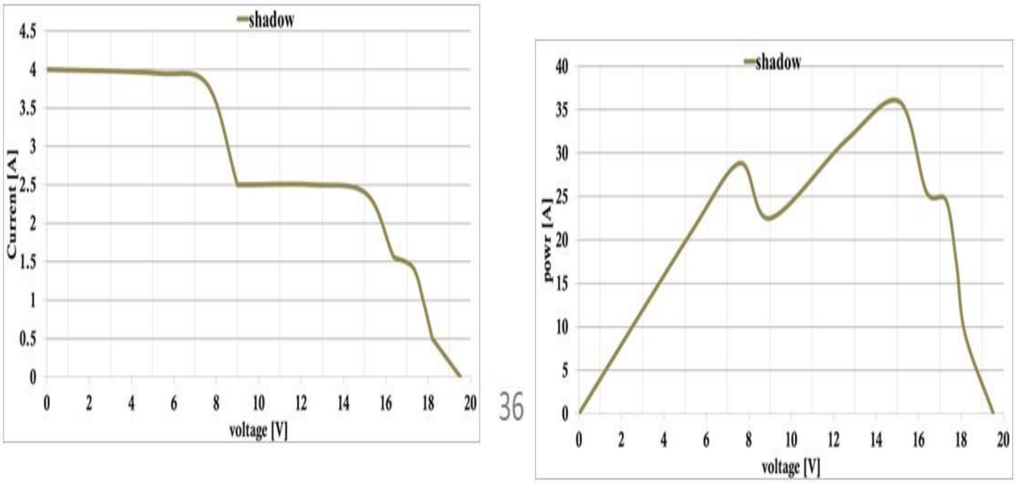


Figure II.12: The impact of partial shading on the PV panels. The I-V curves show large fluctuations and decreases compared to the healthy condition, which can significantly affect the system performance and power output.

II.4.3.Humidity

The two figures represent curves illustrating the effect of humidity on the performance of a photovoltaic system. Figure A shows the relationship between power (in amperes) and voltage (in volts) under the influence of humidity. The power gradually increases with increasing voltage until it peaks at approximately 13.5 V, representing the system's optimal operating point. Beyond this point, the power declines sharply, indicating a decline in efficiency due to the negative effect of humidity or a physical phenomenon that affects performance at higher voltages. Figure B shows the relationship between voltage and current under the same environmental influence. The current begins at a near-constant value (about 4 A) at low voltages up to 7 V, reflecting the stable conductivity region. Thereafter, the current begins to gradually decrease with increasing voltage, due to a change in the electrical properties of the materials affected by humidity, such as increased resistance. Between 13 and 16 volts, a sharp drop in current occurs, indicating the onset of a breakdown or saturation in the system. The drop continues until the current reaches zero at 20 volts, indicating a complete loss of conductivity due to the cumulative effect of moisture and high voltage.

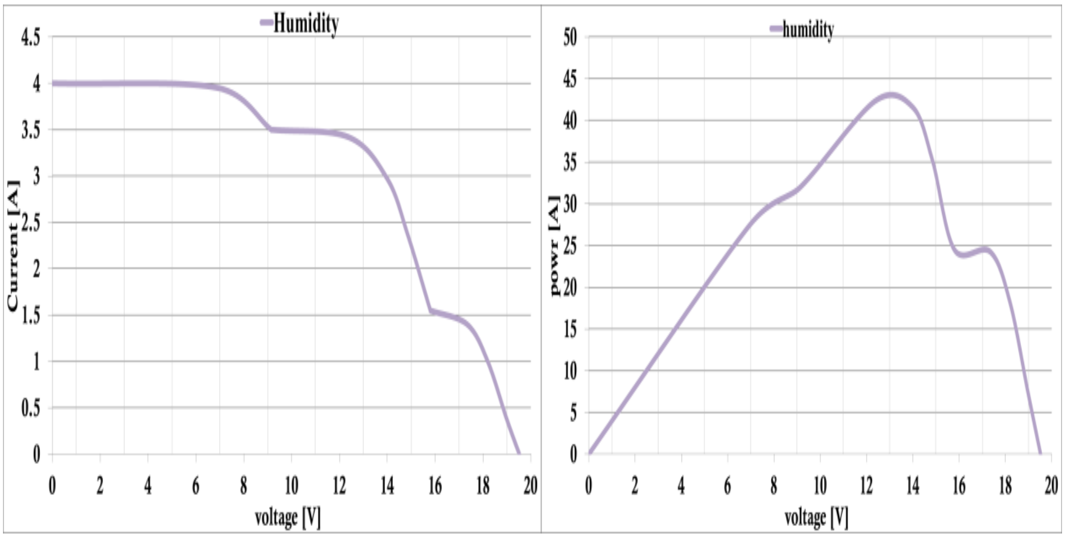
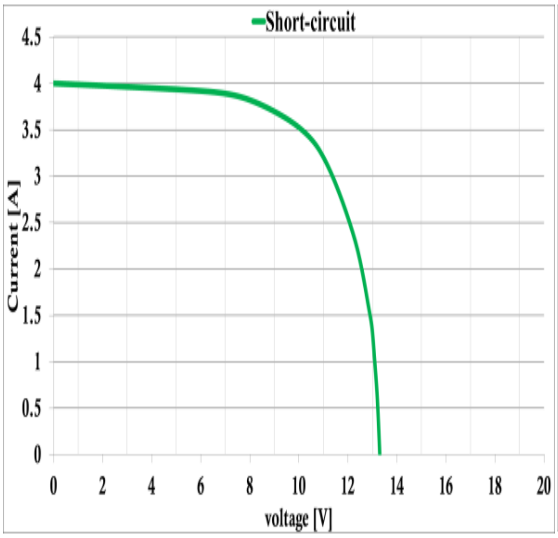


Figure II.13: The impact of the humidity intensity on the PV system. The I-V curves are irregular and show decreased efficiency, indicating the need for moisture protection measures.

II.4.4.Short circuit

The two figures represent curves that reflect the behavior of a photovoltaic system under short-circuit conditions. In the first figure (A), the curve shows the relationship between voltage and power. The power gradually increases with increasing voltage until it reaches a peak at around 11 V, the maximum power point at which the system operates at its most efficient. After this point, a sharp drop in power occurs, indicating a short circuit. A large current flows without a suitable load, resulting in rapid power loss. This abnormal behavior is an indicator of internal faults or damage to the system components and underscores the importance of protection measures and periodic inspection to avoid serious failures. In the second figure (B), we observe the relationship between current and voltage in a solar cell. The current starts at a high value (around 4.2 A) at zero voltage, known as the short-circuit current. As the voltage increases, the current gradually decreases until it reaches almost zero at around 13 V, the open-circuit voltage. The curve shows the steep decline in current before reaching zero. This represents the maximum power point (MPP), which reflects the optimal efficiency of the system under ideal lighting conditions. This figure reflects the typical performance of a solar module and highlights the importance of tracking the MPP to ensure maximum utilization of solar energy.



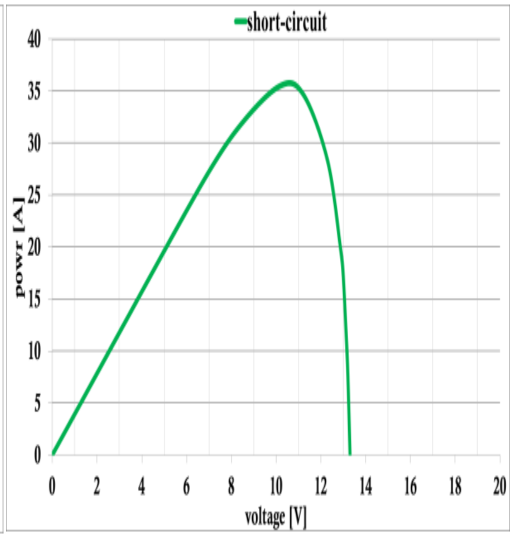


Figure II.14: The impact of short circuit in PV system. The I-V curves exhibit a significant voltage drop which emphasizes the need for regular maintenance.

II.4.5.PV degradation

Figures (A) and (B) illustrate the effect of natural degradation on photovoltaic system performance through two curves reflecting the relationship between voltage and power, and between voltage and current, respectively. Figure (A) shows a gradual increase in power as the voltage increases until the maximum power point (MPP) is reached at approximately 13 V. Then, as the voltage continues to rise, it begins to gradually decline, indicating a decline in system efficiency over time due to natural degradation. This degradation is attributed to environmental factors such as heat, ultraviolet radiation, and humidity, which negatively impact the overall system performance without causing sharp fluctuations in the curve, confirming that the degradation is endogenous and natural.

Figure (B) shows the relationship between current and voltage. The current starts at a high value and remains nearly constant until a voltage of approximately 11 V is reached, then gradually decreases until it reaches zero at the open-circuit voltage. This behavior reflects a gradual degradation of solar cells due to thermal expansion and climatic factors, without sharp breaks. This also indicates natural degradation not caused by sudden failures. Therefore, periodically monitoring these curves is crucial to determine the annual degradation rate, implementing techniques such as MPPT, and improving maintenance plans to ensure the continued operational efficiency of the photovoltaic system.

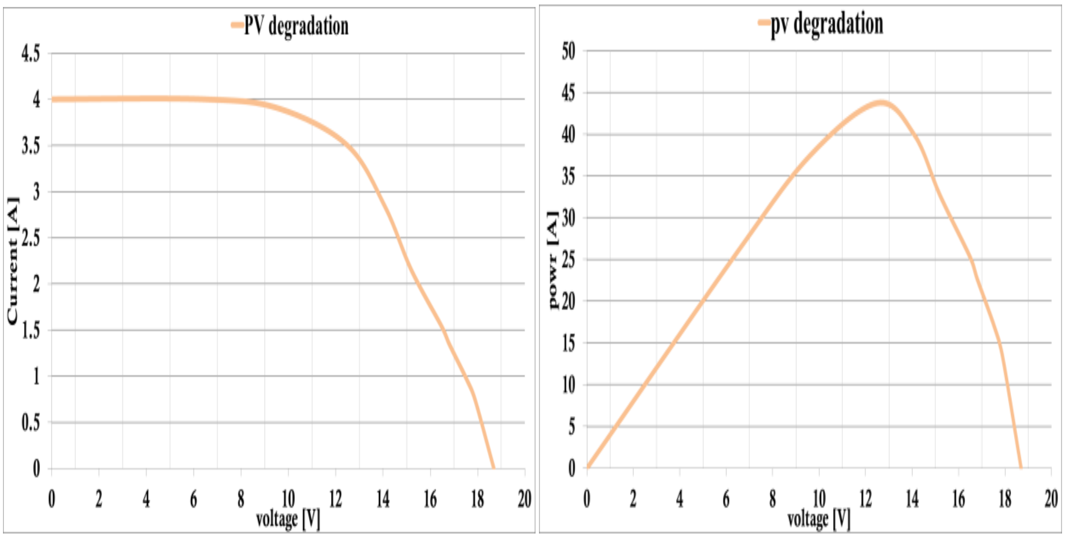


Figure II.15: The impact of degradation of PV panels with time. The I-V curves show a gradual decrease in performance, indicating the importance of timely repair and replacement of old deteriorating components.

II.5.Conclusion

This study emphasizes the importance of system modeling and analyzing external factors to understand and design complex systems. Modeling simplifies reality and predicts system behavior, while analyzing external influences helps identify key impacts on performance. This approach supports informed decision-making and adaptive strategies, ensuring resilient and sustainable systems.

CHAPTER III

Test and Application

III.1. Introduction:

Health monitoring and fault detection in photovoltaic (PV) systems are essential for maximizing efficiency and lifespan. Deviations in current-voltage (I-V) curves indicate potential faults, requiring advanced diagnostic methods. This study presents an AI-enhanced approach combining optimization and classification for accurate fault analysis. A DC/DC buck-boost converter is implemented for real-time I-V data extraction. The proposed method improves reliability and reduces maintenance costs in PV power plants. This research contributes to smarter, more sustainable solar energy management.

III.1.1 Explanation of the applied part

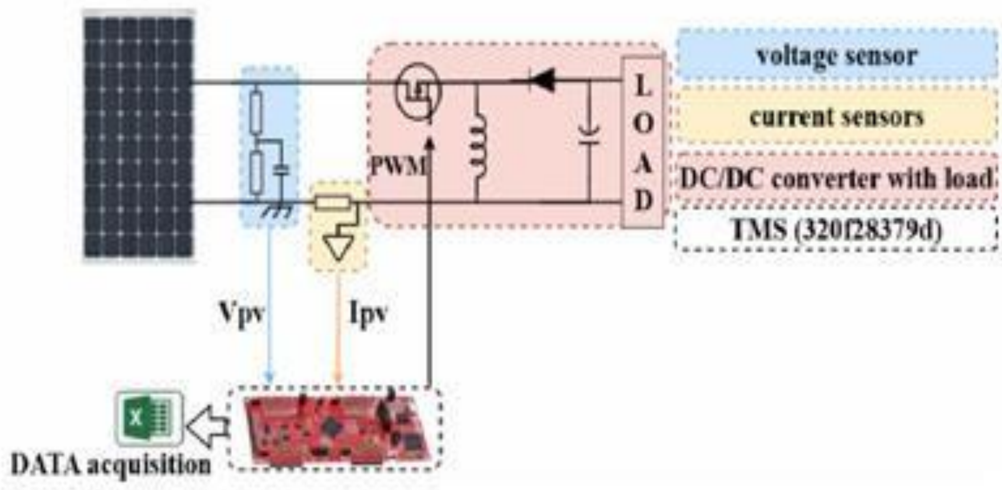


Figure III.1. Proposed Circuit for Extracting Voltage-Current Characteristics Using a DC-DC Buck-Boost Converter.

1. **Main Components in the Circuit** Voltage Sensor:

Measures the voltage (Vpv) coming from a power source such as solar panels or batteries.

Current Sensor:

Measures the current (Ipv) coming from the same source.

Buck-Boost DC/DC Converter:

Used to convert voltage and current to appropriate levels (stepping up or down) depending on the load settings.

Load:

Represents the device or circuit that consumes electrical power, such as a resistor or motor.

TMS Control Module (Reference Number: 320128379d):

power management and control system used to adjust the operation of the Buck-Boost converter, such as changing the duty cycle.

Data Acquisition Module:

Collects readings from sensors and stores them to analyze voltage and current characteristics-.

2. Circuit Operation Steps

•Measuring Source Voltage and Current (Vpv and Ipv)

Sensors measure voltage and current on the primary (source) side of the circuit.

These readings are sent to a data acquisition unit for recording and analysis.

•Power Conversion via a Buck-Boost Converter

The converter operates in either Buck or Boost mode, depending on the load and control settings provided by the TMS.

Buck mode: The voltage is reduced if the source voltage is higher than the load voltage.

Boost mode: The voltage is increased if the load voltage is higher than the source voltage. The conversion ratio is controlled by changing the duty ratio of the PWM signal received from the TMS.

•Connecting the Load

The load is connected to the secondary side of the converter.

The current flowing through the load is determined by the converter's characteristics and control settings.

•Data Collection and Analysis

The data acquisition unit records the voltage and current values on both sides (source and load).

This data is used to plot the voltage-current curve (V-I curve).

3. Steps for Extracting Electrical Characteristics

•Power the circuit and stabilize the power supply (e.g., 24 VDC): Turn on the circuit and ensure that the power supply is stable (for example, 24V DC) so that the measurements are accurate and not affected by fluctuations.

•Gradually change the load (e.g., using a variable resistor) : Slowly vary the load using a variable resistor to observe how the system behaves under different operating conditions.

•Record the Vpv and Ipv values with each load change: For every change in load, measure and record the photovoltaic voltage (Vpv) and current (Ipv).

•Use the TMS module to adjust the converter's operation and maintain system stability: Use the TMS module to control and regulate the converter, ensuring stable operation during the experiment.

•Plot the curve using the recorded data: Use the collected data to draw the voltage-current (V–I) characteristic curve.

•Horizontal axis-Current (Ipv) : The horizontal axis represents the current (Ipv).

•Vertical axis-Voltage (Vpv) : The vertical axis represents the voltage (Vpv).

III .1.2.Experimental Test Bench for Integrating

Figure III.2. Experimental Test Bench for Integrating the PV System and Buck-Boost Converter Controlled by the TMS320F28379D LaunchPad.

in components such as inductors, capacitors, and semiconductor switches. The Buck-Boost curve starts with the load increasing from zero, and at a duty cycle of around 0.5, the PV panel appears directly connected to the load. Beyond this, the Boost mode maximizes power output, covering all functional points and providing a more accurate VI curve compared to using only Boost or Buck converters.

Notes:

The algorithm used in this application is the Perturb and Observe (P&O) algorithm.

Radiation Level :

Radiation Intensity (W/m²)

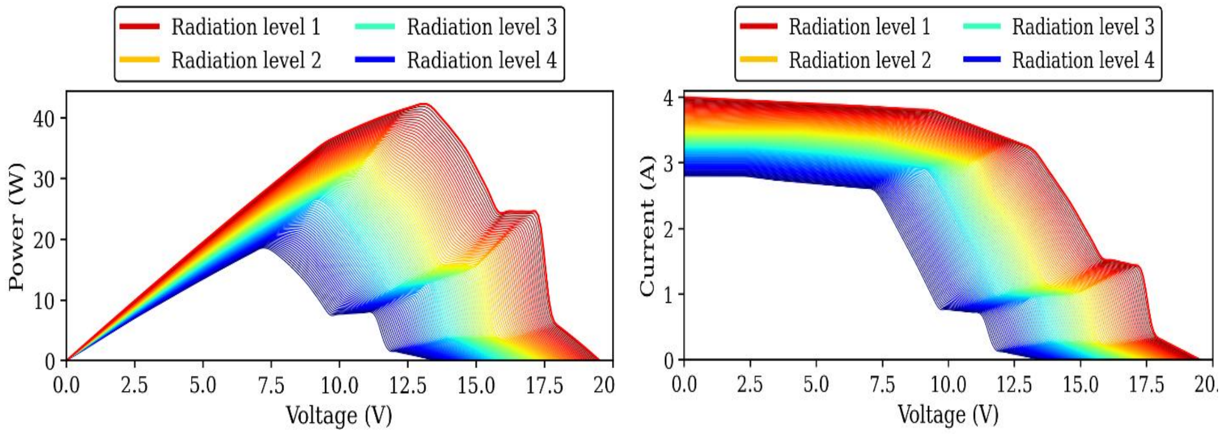
Very High	High	Moderate	Low
Over 1000	700 – 1000	300 – 700	Below 300

III.2.Applied results display

After using the previous device, several results were extracted under several variable conditions, including dust, shade, humidity, short circuit, and deterioration. The analytical results for all phenomena were presented. A curve was extracted. (I-V curve) and (P-V curve)

III .2.1Dust

Figure A (I-V curve) and Figure B (P-V curve) clearly and gradually demonstrate the impact of dust accumulation on photovoltaic performance. In Figure A, we observe a significant decrease in the short-circuit current (Isc) as the dust level increases from level 1 (blue) to level 4 (red), while the open-circuit voltage (Voc) remains relatively constant, indicating that the losses are primarily due to the decrease in the amount of light transmitted to the cell surface.In Figure B, the curve shows a decline in the maximum power point (MPP) and a decrease in the output power with increasing dust accumulation, indicating a direct impact on the efficiency of the photovoltaic system. The maximum power decreases significantly, resulting in operational losses that can reach high percentages if neglected.This deterioration is associated with increased surface resistance caused by the dust layer, as well as reduced photon absorption efficiency, which distorts the performance curves. The analysis highlights the importance of regular maintenance and panel cleaning to maintain stable performance and ensure energy production in dusty environments.

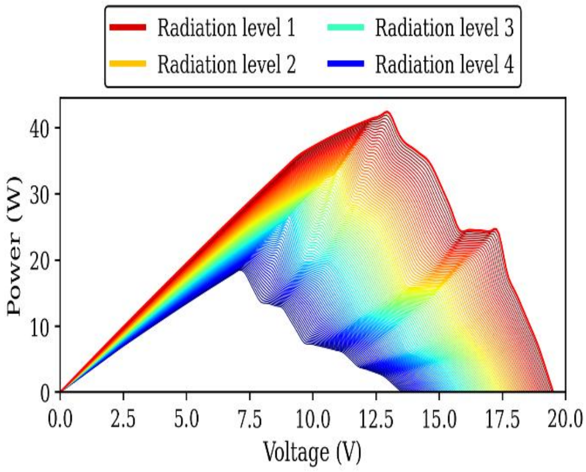


(b) (a)

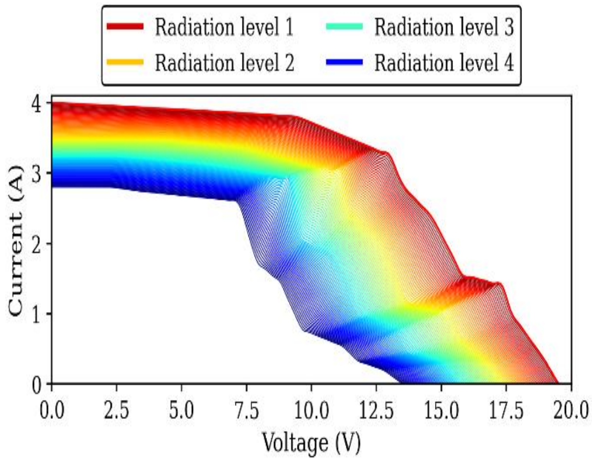
Figure III.3: The effect of dust on solar panels . (I-V curve) and (P-V curve)

III .2.2.Shadow

In Figure (A), which represents the current-voltage (I-V) curve under shade, we observe that the current gradually decreases as solar radiation levels decrease from Level 1 to Level 4. This indicates that solar radiation intensity directly affects the amount of current generated in the solar cell. The maximum cell voltage also gradually decreases with decreasing radiation, indicating poor electrical performance under shaded conditions.Figure (B), which represents the power-voltage (P-V) curve under the same conditions, clearly shows a decrease in the maximum power point (MPP) with decreasing radiation levels. We observe that the highest power is generated at the first radiation level, while it decreases significantly at other levels, reflecting the direct relationship between solar radiation and power output. The shape of the curve also becomes flatter and more distorted at lower levels, making it difficult to track the maximum power point. These results demonstrate that the effect of shadowing has a significant impact on the performance of photovoltaic systems, leading to power losses and altering the electrical output characteristics of the cell. These findings are essential for designing shadow compensation systems or adopting techno logies such as MPPT to ensure optimal operation.



(b)

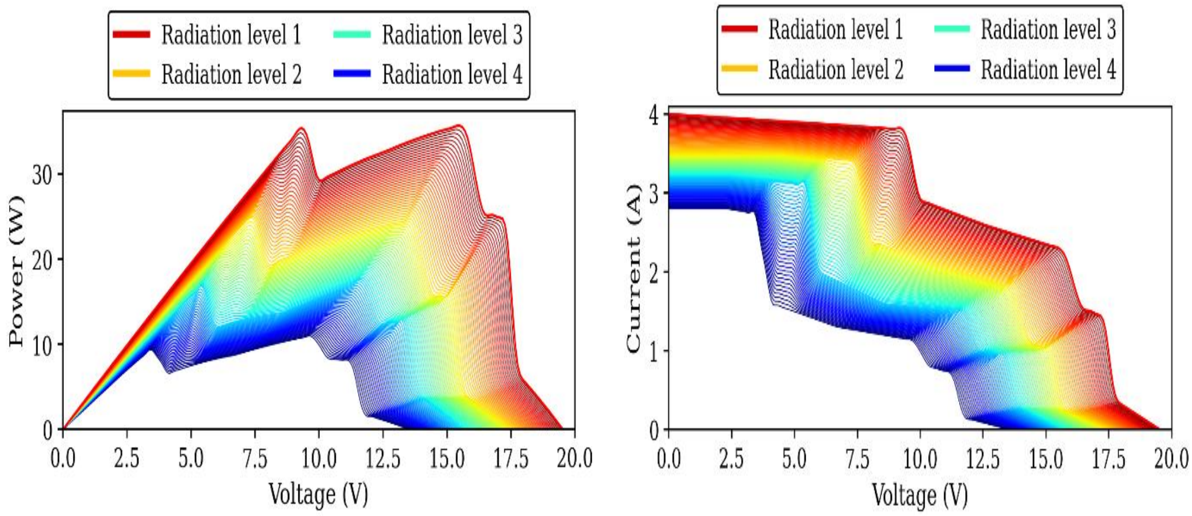


(a)

Figure III.4: The effect of shade on solar panels . (I-V curve) and (P-V curve)

III .2.3.Humidity

Figure (A) shows the current-voltage (I-V) curves under different humidity conditions at four solar radiation levels, while Figure (B) shows the power-voltage (P-V) curves for the same conditions. The results demonstrate that high humidity negatively affects solar cell performance. A clear decrease in current at the same voltage is observed as we move from Level 1 to Level 4, indicating a decrease in photovoltaic efficiency. In Figure (A), the blue curve (Level 1) shows the highest current, indicating the lowest humidity effect, while the red curve (Level 4) shows the lowest current. In Figure (B), the maximum power (Pmax) gradually decreases with increasing humidity, indicating a clear effect on the output power. This decrease in power is associated with a decrease in both voltage and current at the maximum power point. We also note that the shape of the curve becomes less steep and more distorted at high humidity, reflecting the presence of additional losses in the system. These results demonstrate that humidity reduces the efficiency of solar cells due to water vapor absorption of light, reducing the effective radiation incident on the cell, and potentially causing changes in the cell's surface properties. Therefore, humidity control is recommended to improve the performance of photovoltaic systems, especially in regions with humid climates.



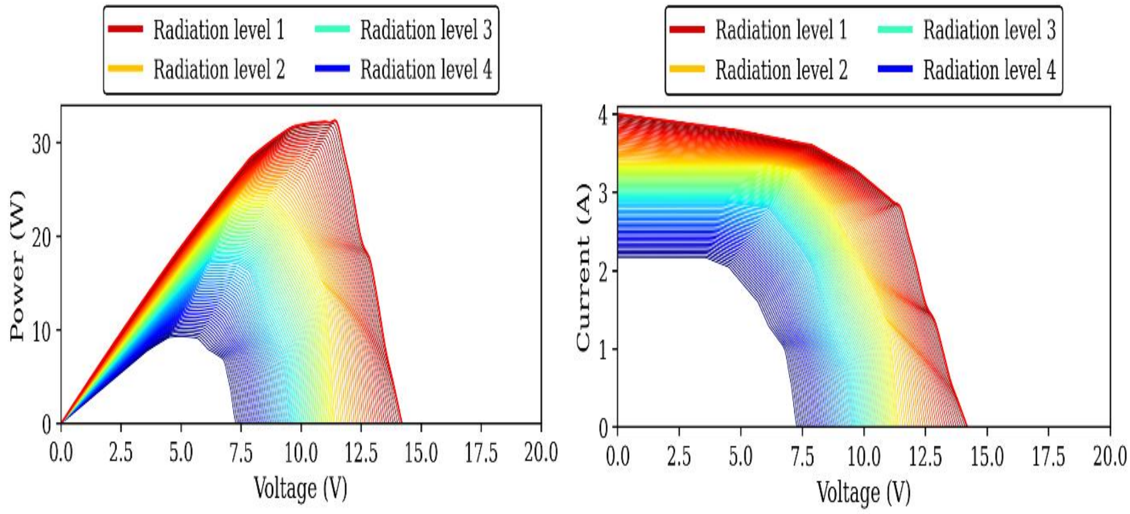
(b) **(a)**

Figure III.5: The effect of humidity on solar panels. (I-V curve) and (P-V curve)

III .2.4.Short circuit

The electrical curves of a solar cell in a short circuit are an important diagnostic tool for understanding the performance of a photovoltaic system. Figure (A) shows the currentvoltage (I-V) curve under varying irradiance levels. The short-circuit current (Isc) increases directly with the intensity of light radiation, reaching its highest value at the maximum irradiance level (Level 4) and its lowest value at the minimum level (Level 1). The curve has a constant linear slope, reflecting the nature of the cell's internal resistance, with a clear intersection with the voltage axis at the theoretical open-circuit voltage. Figure (B) shows the power-voltage (P-V) curve, revealing a nonlinear relationship where the power reaches nearzero values in this case. The curve exhibits an inverted hyperbolic shape with a weak peak representing the transition point between the two modes of cell operation. It is worth noting that the area under the curve is almost zero, indicating a near-total loss of useful electrical power.

These results confirm that short circuits are a practically undesirable situation, as the absence of an effective potential difference prevents the exploitation of the generated photovoltaic energy. They also highlight the importance of short circuit protection systems in practical solar system designs. These curves provide valuable data for energy engineers to understand the internal properties of cells and develop more efficient and safer systems.

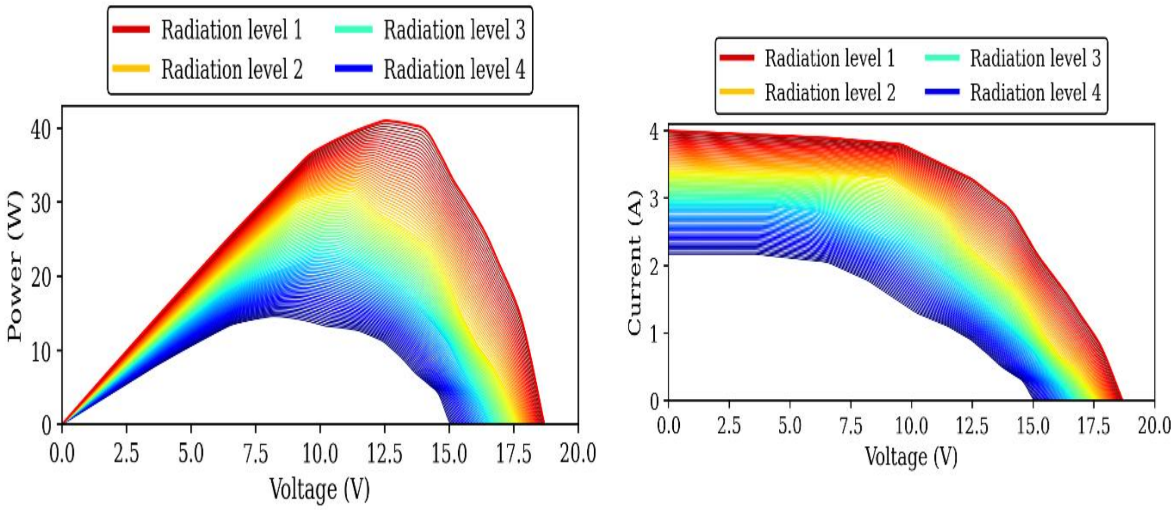


(a) **(b)**

Figure III.6: The effect of short circuit on solar panels (I-V curve) and (P-V curve)

III .2.5.Degradation

Figure A shows the relationship between current (A) and voltage (V) for four irradiance levels (Level 1 to Level 4) under photovoltaic cell degradation conditions. We observe that the current decreases with increasing voltage, a typical behavior for solar cells due to increased internal resistance. Higher irradiance levels (such as Level 1) exhibit higher current at lower voltages, reflecting higher energy conversion efficiency. Degradation is demonstrated by a decrease in current at the same voltage levels compared to ideal conditions, indicating a loss in performance due to factors such as corrosion or cracking. Figure B (P-V Curve) :Figure B shows the relationship between power (W) and voltage (V) for the same irradiance levels. We observe a peak power point (MPP) for each level, whose value decreases as the irradiance level decreases. Degradation is evident by a decrease in the maximum power and its shift toward lower voltages, indicating a loss in efficiency. The curve also shows a variation in the peak shape, becoming flatter with degradation, reflecting increased heat loss or junction resistance. The results confirm that degradation negatively impacts cell performance, as the peak current and power decrease as the curve characteristics change. These analyses are the basis for assessing cell life and improving their maintenance.



(a) **(b)**

Figure III.7: Effect of photovoltaic cell degradation . (I-V curve) and (P-V curve)

III.3.Conclusion:

Through the implementation of a DC/DC buck-boost converter for real-time I-V curve extraction, this study establishes a more accurate diagnostic framework for photovoltaic installations. The fusion of this hardware capability with AI algorithms ensures a high level of precision in identifying system failures. Ultimately, these findings provide a scalable pathway to reducing maintenance complexity and enhancing the economic viability of solar energy through smarter resource management

General Conclusion

General Conclusion

In conclusion, this study has thoroughly examined the impact of various operating condition changes on the performance of photovoltaic cells. Through the analysis of factors such as temperature fluctuations, irradiance levels, and environmental conditions, it is clear that these variables play a crucial role in determining the efficiency and overall effectiveness of photovoltaic systems. By understanding how these conditions affect the conversion of solar energy into electrical power, this research provides valuable insights into optimizing the operation and longevity of photovoltaic cells.

The findings highlight the complex relationship between the operating conditions and the performance of solar cells, emphasizing the importance of careful monitoring and adjustment of these factors to achieve maximum energy production. This study also suggests that further advancements in materials and technology could mitigate some of the negative effects of operating condition variations, leading to more robust and efficient solar energy systems.

Moreover, this research underscores the significance of considering local environmental conditions when designing and deploying photovoltaic systems, especially in regions with fluctuating weather patterns. By integrating this knowledge, we can improve the reliability and performance of solar power generation, contributing to the global shift towards more sustainable energy solutions.

Ultimately, the study serves as a stepping stone for future research aimed at enhancing the efficiency of photovoltaic cells under varying operational conditions, paving the way for more sustainable and economically viable solar energy systems. The insights gained from this study are expected to be valuable for both the academic community and industry professionals working to improve solar technology and its widespread adoption.

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