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Study of the effect of operating condition changes on the performance of photovoltaic cells

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DEDICATION

To those whose prayers were the light that illuminated my path…

To the first person who taught me how to face life, and how faith and hard work are the path to success…

To those who stayed up all night to help me reach where I am today…

To my caring mother and great father, the source of my strength and pride, I dedicate this humble fruit of a long journey filled with diligence and hard work.

To my brothers and sisters, you are my true support and inexhaustible motivation…

To my colleagues and friends who shared my journey of learning and supported me through every moment of doubt and fatigue, my gratitude and appreciation are indescribable.

ZAID Ayoub

DEDICATION

To my beloved parents,

Thank you for your endless love, support, and prayers. Your unwavering belief in me has been my greatest motivation.

To my respected teacher,

I deeply appreciate your guidance, patience, and the knowledge you have shared. You have been a true inspiration.

To my dear friends,

Thank you for your constant encouragement, laughter, and companionship. Your presence has made this journey more meaningful.

With heartfelt gratitude, I dedicate this work to you all.

CHENNOUF Laid

DEDICATION

To those who have been credited after God in my existence and in reaching this stage of my life, to those who have instilled in me the love of knowledge and diligence...

To my dear parents, may God prolong their lives and perpetuate them with a crown over my head.

To those who shared the paths of life with me with their love and support...

To my dear brothers and sisters.

To all those who have helped me and contributed to encouraging me from near or far.

And to every student who seeks knowledge and hopes for success.

I dedicate this humble work.

FARDIA Ali

Abstract

This master's dissertation investigates the effect of changing operating conditions on photovoltaic (PV) cell performance, including temperature, irradiance, dust, shading, humidity, short circuits, and degradation. Using theoretical modeling and experimental validation with a DC-DC buck-boost converter for real-time I-V curve extraction, the study shows that rising temperatures reduce voltage, while lower irradiance decreases current. Dust accumulation and humidity cause light scattering and increased internal losses, reducing power output. Partial shading introduces multiple peaks in P-V curves, complicating maximum power point tracking (MPPT). Short circuits lead to rapid power loss, and long-term degradation shifts the maximum power point toward lower voltages. The findings confirm that environmental factors significantly reduce efficiency and maximum power. The study concludes that regular maintenance, MPPT implementation, bypass diodes, and environmental protection are essential for ensuring system longevity and optimal performance under diverse climatic conditions.

Keywords: Photovoltaic cells, operating conditions, energy efficiency, temperature, irradiance, dust, shading, humidity, degradation, MPPT

Résumé

Ce mémoire de master étudie l'influence des variations des conditions de fonctionnement sur les performances des cellules photovoltaïques (PV), notamment la température, l'éclairement, la poussière, l'ombrage, l'humidité, les courts-circuits et la dégradation. À l'aide d'une modélisation théorique et d'une validation expérimentale avec un convertisseur DC-DC buck-boost pour l'extraction en temps réel des courbes I-V, l'étude montre que l'augmentation de la température réduit la tension, tandis qu'une diminution de l'éclairement diminue le courant. L'accumulation de poussière et l'humidité provoquent une diffusion de la lumière et une augmentation des pertes internes, réduisant ainsi la puissance de sortie. Un ombrage partiel introduit de multiples pics dans les courbes P-V, ce qui complique la recherche du point de puissance maximale (MPPT). Les courts-circuits entraînent une perte de puissance rapide, et la dégradation à long terme décale le point de puissance maximale vers des tensions plus basses. Les résultats confirment que les facteurs environnementaux réduisent significativement le rendement et la puissance maximale. L'étude conclut que la maintenance régulière, la mise en œuvre du MPPT, l'utilisation de diodes de dérivation et la protection de l'environnement sont essentielles pour garantir la longévité du système et des performances optimales dans diverses conditions climatiques.

Mots-clés : Cellules photovoltaïques, conditions de fonctionnement, efficacité énergétique, température, irradiance, poussière, ombrage, humidité, dégradation, MPPT.

ملخص

تبحث هذه الرسالة في تأثير تغير ظروف التشغيل على أداء الخلايا الكهروضوئية، بما في ذلك درجة الحرارة، والإشعاع الشمسي، والغبار، والتظليل، والرطوبة، والدوائر القصيرة، والتدهور. باستخدام النمذجة النظرية والتحقق التجريبي مع محول DC-DC خافض-رافع لاستخراج منحنى التيار-الجهد في الوقت الحقيقي، تُظهر الدراسة أن ارتفاع درجات الحرارة يقلل الجهد، بينما يؤدي انخفاض الإشعاع الشمسي إلى انخفاض التيار. يتسبب تراكم الغبار والرطوبة في تشتت الضوء وزيادة الخسائر الداخلية، مما يقلل من إنتاج الطاقة. يُدخل التظليل الجزئي قممًا متعددة في منحنيات القدرة-الجهد، مما يُعقد تتبع نقطة القدرة القصوى. تؤدي الدوائر القصيرة إلى فقدان سريع للطاقة، ويؤدي التدهور طويل الأمد إلى إزاحة نقطة القدرة القصوى نحو جهود أقل. تؤكد النتائج أن العوامل البيئية تقلل بشكل كبير من الكفاءة والقدرة القصوى. تخلص الدراسة إلى أن الصيانة الدورية، وتطبيق تقنية تتبع نقطة القدرة القصوى (MPPT)، واستخدام ثنائيات التجاوز، وحماية البيئة، أمورٌ ضرورية لضمان عمر أطول للنظام وأدائه الأمثل في ظل ظروف مناخية متنوعة.

الكلمات المفتاحية: الخلايا الكهروضوئية، ظروف التشغيل، كفاءة الطاقة، درجة الحرارة، الإشعاع الشمسي، الغبار، التظليل، الرطوبة، التدهور، تقنية تتبع نقطة القدرة القصوى (MPPT).

List of Figures

Content

Introduction générale

Photovoltaic (PV) cells, often referred to as solar cells, play a pivotal role in the global transition towards sustainable energy sources. These devices convert sunlight directly into electricity through the photovoltaic effect, making them a key component of renewable energy systems. With the increasing demand for clean and sustainable energy, the performance of PV cells has gained significant attention, not only due to their potential to reduce reliance on fossil fuels but also for their role in mitigating environmental pollution and addressing climate change.

However, the efficiency and overall performance of photovoltaic cells are highly influenced by various operating conditions. These conditions include factors such as temperature, solar irradiance, angle of incidence, and environmental factors like dust accumulation and humidity. As these variables change, they directly impact the electrical output of PV systems. The sensitivity of PV cells to these factors necessitates a comprehensive understanding of how operating conditions affect their efficiency and power output.

The effect of temperature, for instance, is one of the most critical factors affecting PV performance. Higher temperatures typically lead to a decrease in the voltage output of solar cells, despite an increase in the intensity of solar radiation. Similarly, variations in solar irradiance impact the current generated by the cells. Understanding these relationships is crucial for optimizing the operation of photovoltaic systems, especially in regions with extreme climate conditions.

This study aims to investigate the impact of various operating condition changes, including temperature fluctuations, variations in solar irradiance, and the effects of shading and dirt on the surface of PV cells, on the performance of these devices. Through a detailed analysis of these factors, the study seeks to develop strategies to enhance the performance and reliability of PV cells, thereby improving their efficiency and longevity in diverse environmental conditions. By understanding how these changes influence the output of PV cells, the study will contribute to the development of more effective and sustainable solar energy solutions. The findings of this study have important implications not only for the performance of individual photovoltaic systems but also for the broader field of solar energy applications, particularly in optimizing energy production, reducing maintenance costs, and extending the lifespan of PV systems. The insights gained could be instrumental in the design of more efficient solar power plants and for informing policies that promote the adoption of solar energy globally.

Etude bibliographique

CHAPTER I

Solar Radiation and Photovoltaic Energy

I.1. Introduction :

Solar radiation, the most abundant energy resource on Earth, is the primary source of energy for photovoltaic (PV) systems. Photovoltaic energy, often referred to as solar energy, is harnessed through the use of photovoltaic cells, which convert sunlight directly into electricity.

In this chapter, we will discuss general information about solar energy. We will describe the basic concepts of photovoltaic systems and electricity production through the photovoltaic effect. We will explain how solar energy varies depending on location and season.

I.1 Overview and Motivation

The increasing global demand for electrical energy, predominantly derived from fossil fuels such as oil and coal, has placed considerable pressure on fossil fuel reserves and has significantly impacted the global environment. The limited supply of fossil fuels, which remain the predominant energy source, results in substantial greenhouse gas emissions, including nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), that are key contributors to climate change (IPCC, 2007).

Furthermore, the use of fossil fuels for transportation and the ongoing expansion of industrial activities have led to severe air pollution, compounding environmental challenges [1, 2] . To sustain economic growth while safeguarding natural ecosystems for future generations, it is imperative to transition to alternative, sustainable, and clean energy sources. Achieving these goals necessitates coordinated global efforts, as emphasized in international frameworks like 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.

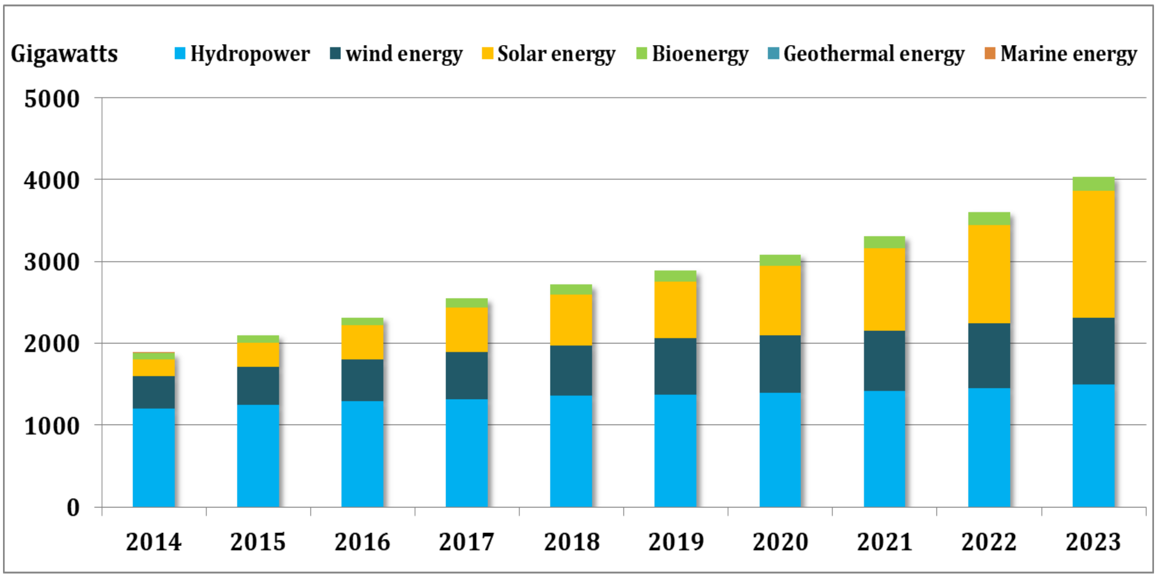


Figure 1.1 Global power generating capacity [4].

Among renewable energy technologies, solar photovoltaic energy and wind power have experienced substantial growth, outpacing other forms of RES. As shown in Figure 1.2, photovoltaic systems (PV) and wind power constitute approximately 33% and 28% of new renewable energy installations, respectively. This trend underscores the potential of these technologies to play a leading role in decarbonizing the energy sector. The geographical potential for solar energy, in particular, varies significantly by region, as illustrated in Figure 1.3.

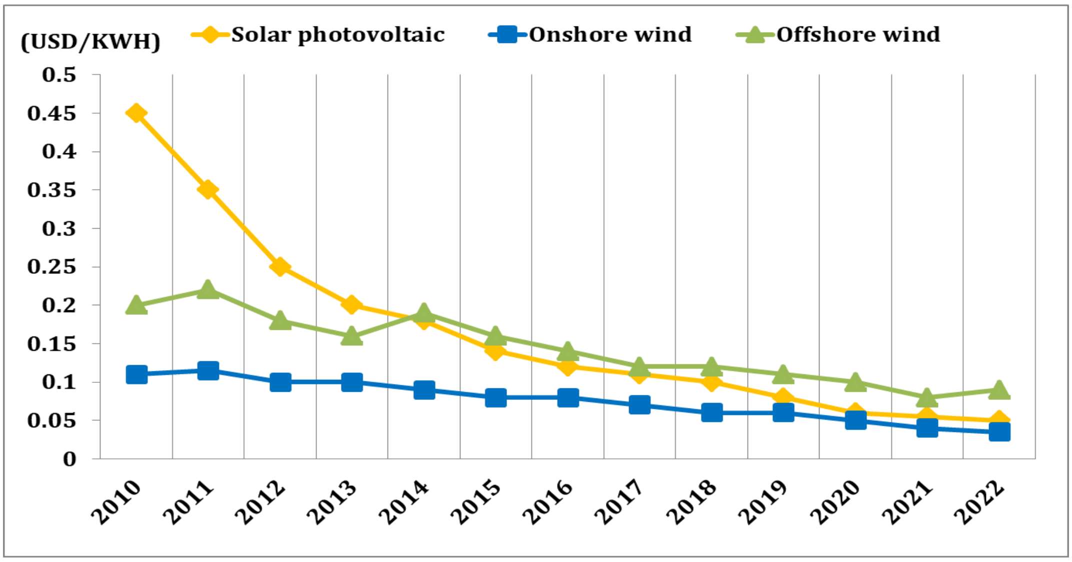


Figure 1.2 Levelised cost of electricity from newly commissioned solar PV, onshore wind power and offshore wind power, 2010-2022 [5].

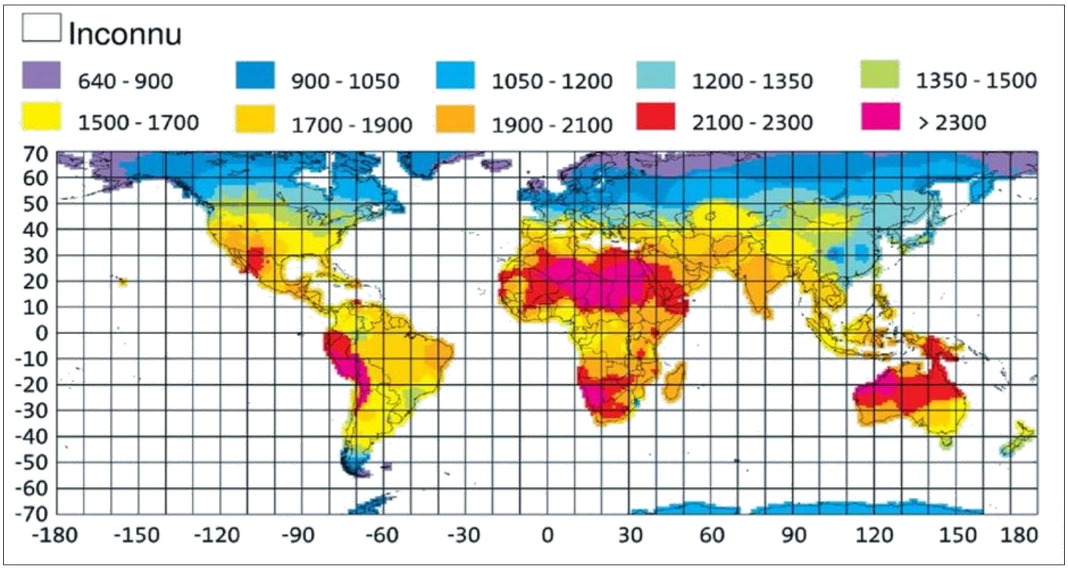


Figure 1.3 Solar irradiation map of the world from photovoltaic guidenr.

The levelized cost of electricity (LCOE) associated with renewable energy technologies has experienced a substantial decline in recent years. Among these, onshore wind energy has exhibited the most pronounced reduction, with the global average LCOE decreasing by 50% between 2010 and 2022 to reach USD 0.033 per kilowatt-hour (kWh). Similarly, solar photovoltaic (PV) systems have observed a significant cost reduction, with the global average LCOE recorded at USD 0.049 per kWh in 2022. In contrast, offshore wind energy remains comparatively more expensive, with an LCOE of USD 0.081 per kWh (refer to Figure 1.2).

Despite these advancements in cost-efficiency, the integration of renewable energy sources, particularly solar PV, into the power grid presents notable challenges due to their intermittent nature. The direct current (DC) voltage output from these systems is inherently variable, influenced by fluctuating environmental conditions, which renders direct grid connection impractical. This challenge has catalyzed advancements in power electronic converters (PECs) as a pivotal technological solution.

Power electronic converters serve as intermediary devices between renewable energy systems and the electrical grid. These converters address the variability of output voltage by dynamically regulating it, ensuring efficient power conversion, and maintaining a balanced power distribution. Through these functions, PECs enhance grid compatibility and ensure the reliable delivery of power generated from renewable sources.

I.2 Power Electronics Converters for Renewable Energy System

Power electronic converters (PECs) are essential in facilitating the integration of renewable energy sources (RES) with the electrical grid or load systems. Their operation critically impacts the overall performance of the system, particularly influencing aspects such as stability, reliability, efficiency, power quality, and the consumption ratio.

To ensure energy conversion processes that are both cost-effective and efficient, various innovative Photo electrochemical (PEC) systems are being developed alongside the increasing practical implementation of renewable energy technologies [4]. Figure 1.4 presents a detailed framework for the integration of Renewable Energy Sources (RES) through the application of Power Electronic Converters (PEC). The incorporation of RES into electrical systems necessitates the deployment of PEC to align the outputs of RES with the requirements of the power grid. Consequently, significant advancements have been made in enhancing the efficiency of PEC systems. These improvements can be achieved through two primary approaches: (a) the development of novel power converter designs or (b) the implementation of advanced control strategies.

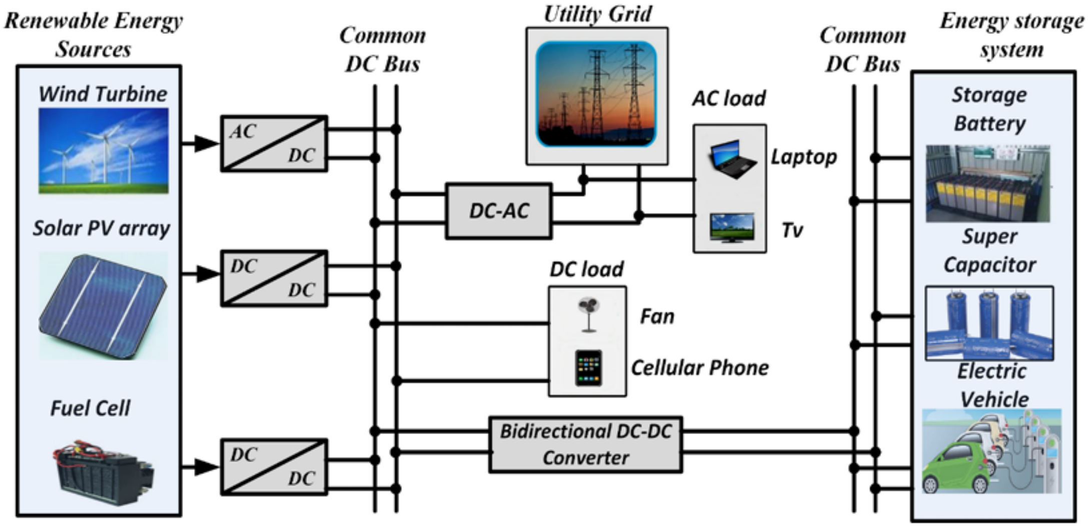


Figure 1.4 Schematic exhibiting the relationship of a RES to the electricity grid.

The classification of converters in renewable energy systems (RES) encompasses two primary categories: galvanic ally isolated and non-isolated variants [6], [7]. Galvanically isolated converters, also known as transformer-based converters, employ a transformer to achieve input-output isolation, as highlighted in the topological analyses of [8],[9], [10]. This isolation mechanism enhances their functional potential. However, the inclusion of transformers introduces notable challenges, including increased financial costs, larger physical dimensions, and reduced operational efficiency. These limitations, absent in non-isolated or transformer-less solutions, are substantiated by empirical findings from case studies [11, 12]. Therefore, non-isolated converters emerge as a more favorable option in power conversion processes when all critical factors are considered.

I.2.1 Review of PV Energy System Applications

Photovoltaic (PV) energy conversion systems play a crucial role in the integration of renewable energy into the utility grid, providing a sustainable and efficient solution for electricity generation. Figure 1.5 illustrates the structural configuration of such a system, beginning with PV arrays that harvest solar irradiance and convert it into direct current (DC) electrical energy, which is subsequently stabilized via DC bus structures. A multilevel power electronics converter serves as the pivotal component, facilitating the conversion of DC power into alternating current (AC) power characterized by high quality and reduced Total Harmonic Distortion (THD). A filtering stage ensures compliance with grid standards by attenuating high-frequency noise, while an optional transformer is incorporated to perform voltage adaptation and provide electrical isolation between the PV system and the grid. The control unit, incorporating a Maximum Power Point Tracking (MPPT) controller, ensures optimal energy harvesting from the PV arrays and precise regulation of the power electronics converter. Ultimately, the AC power is injected into the utility grid, demonstrating a sophisticated integration of advanced control algorithms and power conversion technologies for efficient solar energy utilization and grid compatibility.

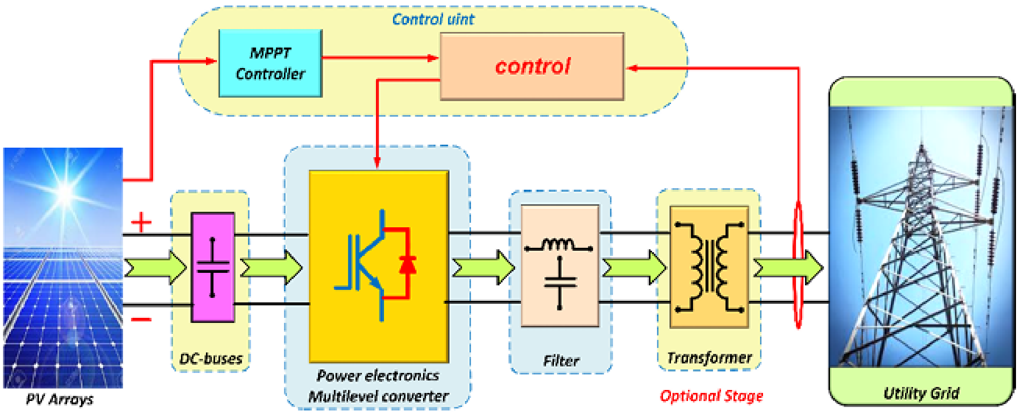


Figure 1.5 a photovoltaic (PV) system with power electronics and the needed control.

I.2.2 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.2.3 Classification of DC–DC converters

Many researchers have addressed different types of DC–DC converters for renewable energy applications and storage to improve and enhance efficiency whilst overcoming the weaknesses of converters. DC–DC converters are categorized into three major technologies based on their operation modes, as shown in Figure 2 [13-15]. They are linear mode, hard switching mode, and soft switching mode. The linear mode has features such as sim plicity, low noise with good regulation, and quick response. On the other hand, its drawback is low efficiency due to power losses in various working conditions. Hard switching mode converters can be sub-categorized into non-isolated and isolated converters based on galvanic isolation. The buck, boost, buck–boost, and Cuk converters are typical examples of the hard switching mode topologies that are without galvanic isolation (non-isolated) and identified as chopper circuits. However, galvanic isolation (transformer) is necessary for safety causes when the converters are supplied by the utility grid. Power converters (PCs), with their control techniques, help regulate voltages of nodes in microgrid with different types of loads such as resistive, inductive, nonlinear, constant power, or critical loads. However, constant power loads (CPLs) affect the stability of the voltage in the output of PCs and are usually difficult to regulate with traditional control techniques [16, 17].

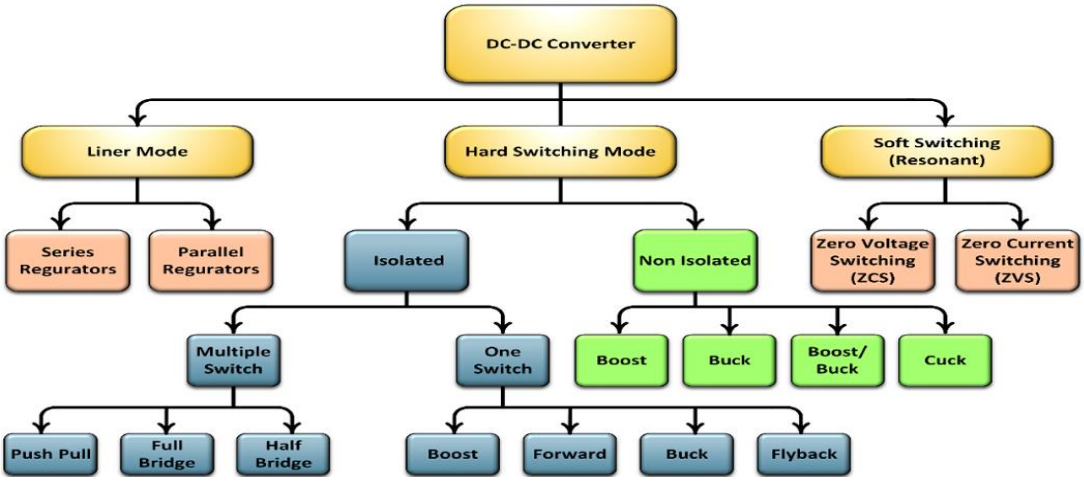


Figure 2: Classification of DC–DC converters [18].

I.2. Solar Radiation :

Solar radiation refers to the entirety of the radiations emitted by the Sun. In addition to cosmic rays, particles characterized by extremely high speed and energy, the Sun emits electromagnetic waves that extend from the radio wave spectrum to gamma rays, passing through visible light.

The emission of electromagnetic waves by the Sun is accurately modelled by a black body at 5800 Kelvin, as described by Planck's law. The emission peak is in the yellow spectrum (λ=570 nm), with radiation distribution roughly evenly split between visible light and infrared, and 1% in ultraviolet. Upon reaching sea level, after traversing the entire Earth's atmosphere, solar radiation undergoes several "filtering" processes. Notably observable in the spectrum are the ozone absorption bands (known to absorb a significant portion of ultraviolet radiation), oxygen, carbon dioxide, and water [1] .

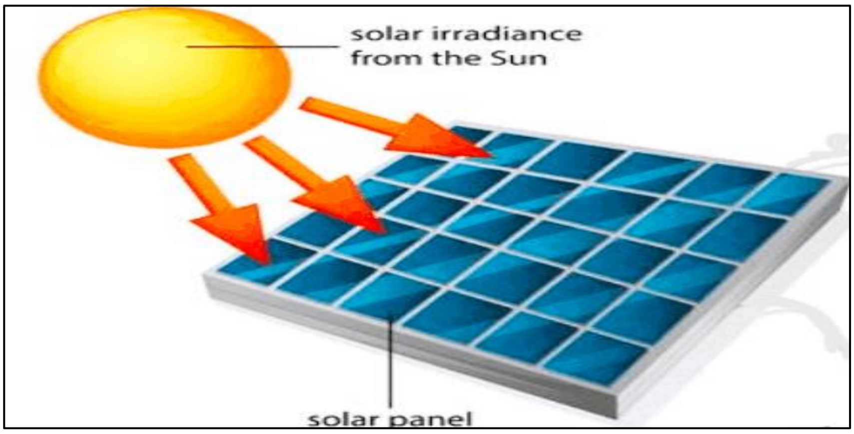


Figure (1.1): Representation of Solar Radiation

I.3. Radiation Spectrum:

The concept of solar energy may seem abstract, but in reality, it’s what we have always known as heat and light from the Sun The invention of photovoltaic cells last century gave us the possibility of powering our civilization with solar energy. With photovoltaic solar panels, light energy is converted into a flow of electricity.

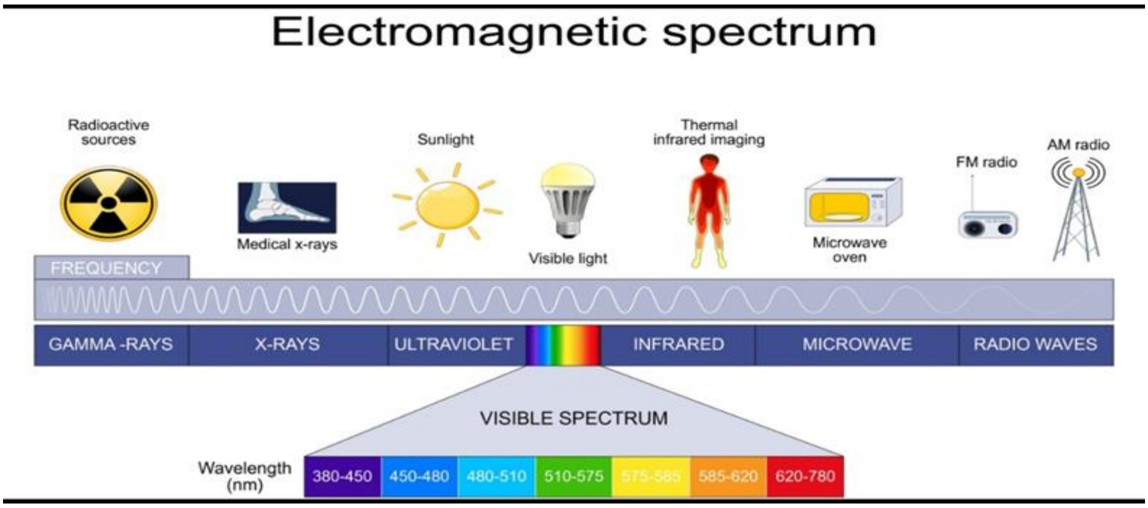


Figure (1.2): Solar Radiation Spectrum

While the electromagnetic spectrum is wide and vast, 99.8% of the Sun’s radiant energy is emitted in a very narrow bandwidth from 20 to 2500 nanometers.

Only a small fraction of solar radiation reaches the Earth's surface, including radio waves with a wavelength of a few decameters to the softest ultraviolet rays, while the rest is either reflected or absorbed by the atmosphere and ionosphere [2].

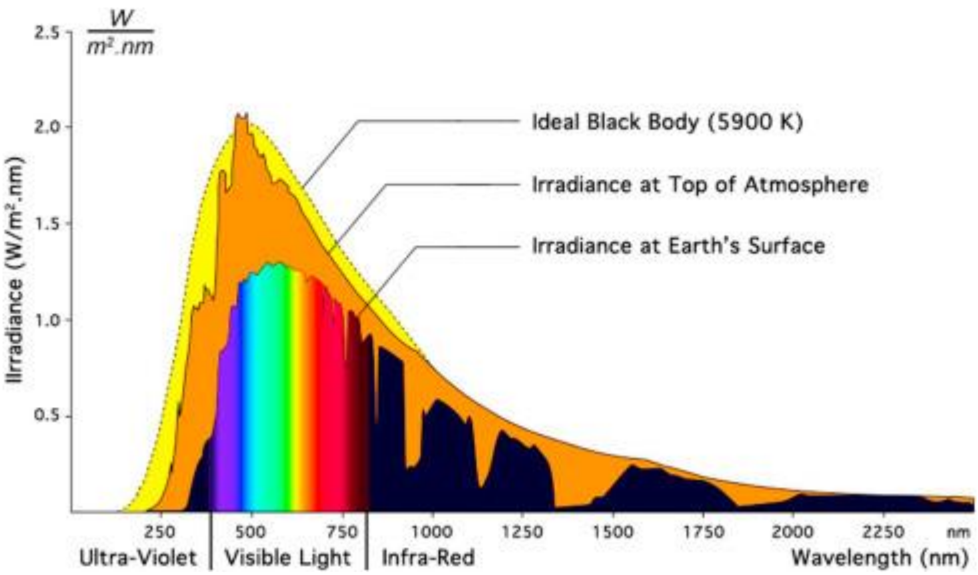


Figure (1.3) illustrates the solar radiation spectrum.

The composition of solar energy is approximately 5% ultraviolet light; 42% visible light and 53% near infra-red radiation.

I.4. Conversion of Solar Radiation by PV Effect:

A PV cell consists of two layers of silicon; these two layers are doped to be polarized. To make one of the layers positive ("P layer"), a certain number of boron atoms are incorporated, and to make the other layer negative ("N layer"), a certain number of phosphorus atoms are incorporated. This creates a potential barrier. When a photon with sufficient energy is absorbed by this semiconductor, it breaks a valence bond and releases an electron, creating a positive "hole". This is what is called the photovoltaic effect: it is the potential difference between these two layers. By connecting the two layers, there is a movement of electrons from one layer to the other, thus creating an electric current [1].

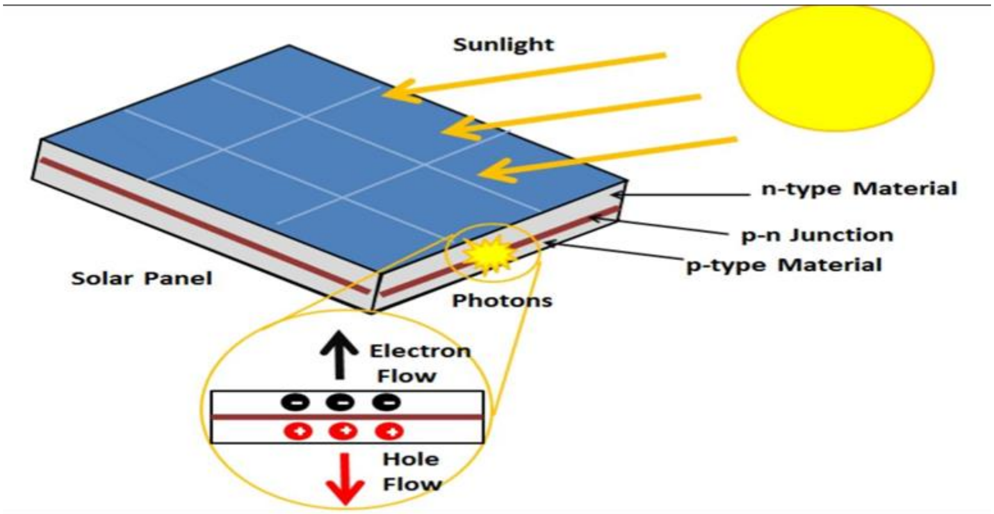


Figure (1.4): Solar Radiation Conversion by PV Effect.

I.5. Photovoltaic Generator:

The photovoltaic sensor is characterized by its electrical properties, particularly the relationship between current and voltage (I=f (V)), as illustrated in Figure (1.5).

This modelling is commonly used to estimate the sensor output (voltage, current) based on two input variables: temperature and the illumination received by the sensor.

The current produced by the photovoltaic module at a given voltage depends exclusively on the illumination and the temperature of the cell. With temperature and illumination constant, the efficiency of a solar cell is influenced by the load present in the electrical circuit.

In an open circuit configuration ($R_c = \infty$, I = 0, V = V_{oc}) or a short circuit (R_c = 0, I = I_{cc}, V = 0), no energy is transmitted outside. Between these two extremes, an optimal value R_{opt} of the load resistance Rc exists, for which the power

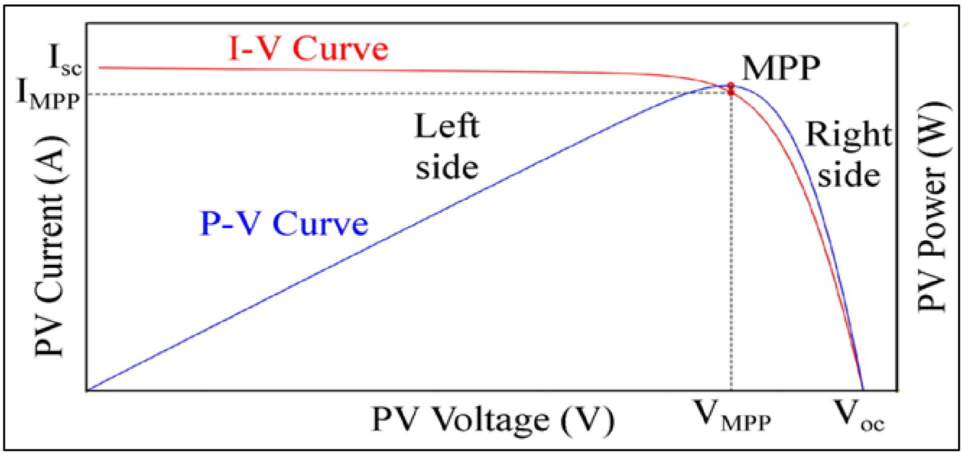


Figure (1.5): Typical Characteristics of a PV Generator.

($P=V_{max} \times I_{max}$) provided by the solar cell to the load resistance is maximal, thus reaching P_{max} [2].

The energy efficiency of the solar cell is defined as $\eta=P/P$, where $P\gamma$ is the incident light power on the surface of the cell. For the optimal value R_{opt} of the load resistance R_c, the efficiency of the solar cell is maximum, and $\eta_{max}=P_{max}/P\gamma$. The value of R_{opt} 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.).

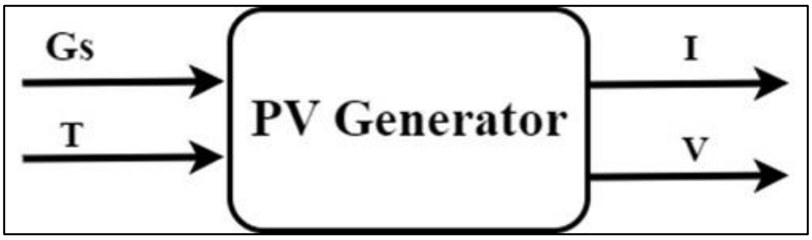


Figure (1.6): Block Diagram of a PV Generator.

I.5.1. Photovoltaic Cell:

Photovoltaic modules consist of an arrangement of interconnected solar cells. These cells are embedded in resin and encapsulated between two tempered glass panes (double-glass modules) or between a glass pane and a Tedlar sheet (glass/Tedlar module). Typically, this assembly is inserted into an anodized aluminium frame, although frameless modules are available for building integration applications, using aluminium profiles on facades or roofs. The power that a module can provide depends on its surface area and the incident solar irradiation, expressed in peak watts (W_p), and represents the maximum power of the module for a reference maximum solar irradiation (1000 W/m^2).

The voltage delivered by a module depends on the number of cells connected in series. For low-power modules (< 75 W_p), the operating voltage is generally between 12 and 15 volts. Higher power modules are obtained by increasing the number of cells in series, which results in an "increase in voltage," and by increasing the number of cell branches in parallel, which causes an "increase in current value." The operating voltage can then be 24 volts or more, depending on the system configuration to be powered. The surface area of the modules varies among manufacturers, typically between 0.5 and 1 square meter; it can reach 3 square meters for special productions and large orders. Several interconnected modules form a panel, and several interconnected panels make up a photovoltaic array. Assembling modules in series and/or in parallel allows generating different voltages and powers [1].

I.5.2. Modelling of a PV Cell:

The operation of a photovoltaic module is described by the "standard" one-diode model, established by Shockley for a single photovoltaic cell, and then generalized to a photovoltaic module by considering it as a set of identical cells connected in series or parallel.

In the literature, a photovoltaic cell is often described as an electrical current generator whose behaviour is equivalent to a current source shunted by a diode. To account for physical phenomena at the cell level, the model is supplemented by two series resistances R_s and R_{sh}, as illustrated in the equivalent circuit diagram in Figure (1.7).

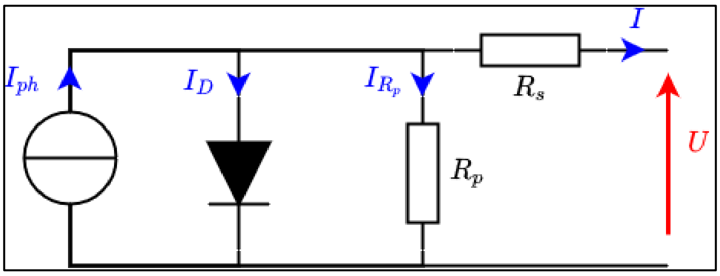


Figure (1.7): Equivalent Circuit of a PV Cell.

The series resistance represents the internal resistance of the cell and depends mainly on the resistance of the semiconductor used, the contact resistance of the collecting grids, and the resistivity of these grids. The shunt resistance is due to leakage current at the junction and depends on how it was made.

I.6. Types of Photovoltaic Cells:

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

1. Monocrystalline Cells: Monocrystalline silicon results from the cooling of molten silicon. Once solidified, it transforms into a uniform crystal that is cut into thin slices to form the photovoltaic cell. The colour of this material is blue, without any trace of crystals or other impurities.

Figure (1.8): Monocrystalline Cells

2. Polycrystalline Cells: Polycrystalline silicon is obtained by melting silicon in a square and elongated metal mold, called an ingot. The color of this type of cell is blue and speckled with patterns left by the crystals. This characteristic allows us to easily recognize this photovoltaic cell.

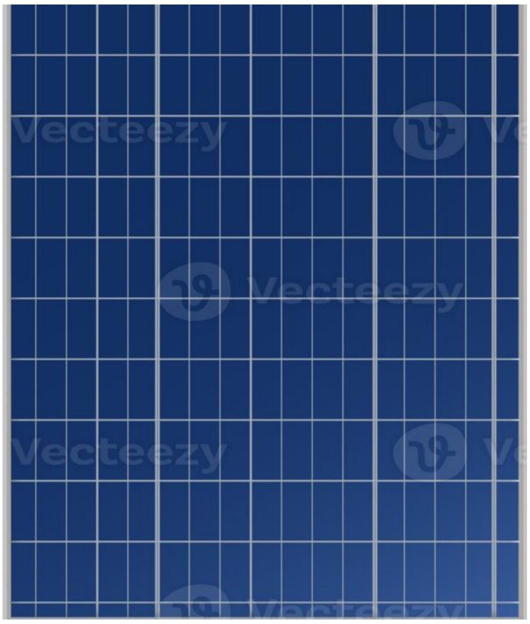


Figure (1.9): Polycrystalline Cells

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 (1.10): Hydrogenated Amorphous Cells.

I.7. the Impact of Temperature on Solar Panel:

Temperature has a significant impact on the performance of solar panels. Here's how:

- **Reduction in Efficiency:** As the temperature of solar panels increases, their efficiency decreases. Solar panels work by converting sunlight into electricity, and as the temperature rises, the efficiency of this conversion decreases.
- **Voltage Decrease:** The voltage of a solar panel decreases as its temperature increases. This is due to the fact that the semiconductor material in solar panels becomes less efficient at transporting charges as temperature increases.
- **Power Output Reduction:** Higher temperatures can lead to a decrease in the power output of solar panels. This is because the decrease in efficiency and voltage negatively impacts the overall power output.
- **Thermal Degradation:** High temperatures can cause thermal degradation of solar panel materials over time, reducing their lifespan and efficiency.
- **Operating Temperature Range:** Solar panels are designed to operate within a certain temperature range. If temperatures exceed this range, the performance of the panels can be further compromised.

Overall, while solar panels still generate electricity on hot days, their efficiency decreases as temperatures rise, impacting their overall performance and output.

I.7.1. Advantages and Disadvantages of PV Energy:

Advantages:

- **Renewable Energy**: Solar energy is an abundant and widely available renewable resource worldwide, making it a sustainable long-term energy source.
- **Low Greenhouse Gas Emissions**: Solar energy does not produce greenhouse gases during its use, helping to reduce carbon emissions and mitigate climate change.
- **Decreasing Costs**: The costs of solar technologies have significantly decreased over the years, making solar energy increasingly competitive compared to conventional energy sources.
- **Energy Independence**: Photovoltaic systems allow users to produce their own electricity, reducing their dependence on energy suppliers and market price fluctuations.

- **Low Maintenance**: Solar installations require minimal maintenance once installed, reducing long-term maintenance costs.

I.7.2. Disadvantages:

- **Sunlight Variability**: Solar energy depends on the availability of sunlight, making photovoltaic electricity production variable and intermittent, often requiring energy storage or integration with other energy sources.
- **High Initial Costs**: Although the costs of solar technologies have decreased, initial investments in solar installations can still be relatively high.
- **Environmental Impact**: While solar energy is generally considered clean, the manufacturing and disposal of solar panels can have an environmental impact.
- **Space Requirement**: Solar installations often require large land or roof areas to accommodate solar panels, which can pose challenges in densely populated urban areas or areas with limited space.
- **Dependency on Weather Conditions**: Solar system performance can be affected by weather conditions such as clouds, rain, or snow, which can reduce the efficiency of solar electricity production at certain times.

I.8. Conclusion:

In conclusion, this chapter covered the fundamentals of solar radiation and photovoltaic energy conversion. It explained how solar cells harness the photovoltaic effect to generate electricity from sunlight.

The modeling and characteristics of photovoltaic generators were discussed, including factors influencing their efficiency like temperature and load resistance. Different types of photovoltaic cells based on silicon crystal structure were presented.

The chapter also touched upon the components of photovoltaic modules and highlighted the key advantages and disadvantages of solar photovoltaic technology.

CHAPTER II

Analysis of Experimental Results

II.1. Introduction

System modeling is essential for understanding and predicting the behavior of complex systems in fields like engineering, economics, and environmental science. It involves creating abstract representations to study system dynamics and interactions, aiding in decision-making and risk mitigation. However, external factors such as environmental changes, economic shifts, or technological advancements can significantly influence system behavior. Incorporating these factors into models is crucial for improving their accuracy and reliability.

This introduction emphasizes the importance of system modeling and the role of external factors in enhancing predictive capabilities and managing complex systems effectively.

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:

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

As the surface area of the cells increases, the current produced by a single cell steadily increases with technological advancements, while its voltage remains very low.

The series connection thus allows for an increase in the overall voltage, thereby enhancing the total power output.

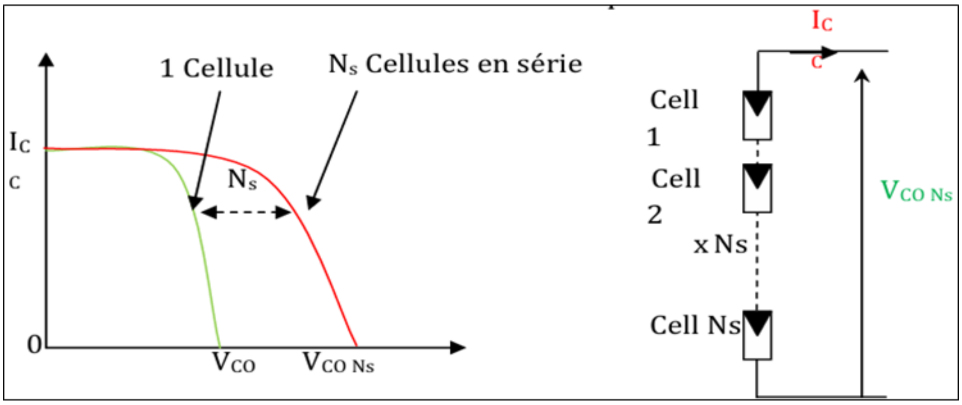


Figure II.1: Resulting characteristic of a series connection of (Ns) cells.

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.

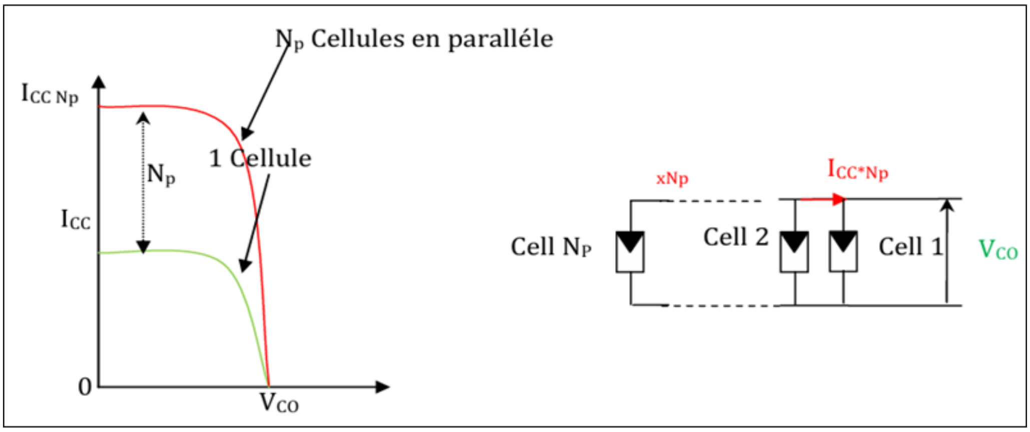


Figure II.2: Resulting characteristic of a parallel connection of (Np) cells [41].

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

$V_{ocNp} = V_{oc}$ 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:

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

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

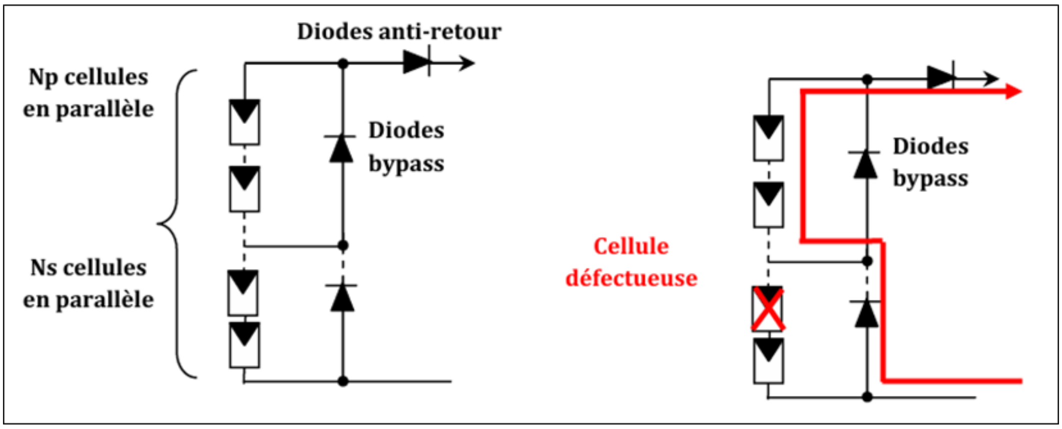


Figure II.3: Resulting characteristics of a hybrid connection of ($Ns\ x\ Np$) cells [41].

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.

Thus, the characteristic $Ip\ Vp$ of a photovoltaic generator can be considered the result of a network of $Ns\ x\ Np$ cells connected in series/parallel.

The overall characteristic can also vary depending on illumination, temperature, cell aging, shading effects, or illumination inhomogeneity. Furthermore, even single shading or degradation of a cell in a series connection can cause a significant reduction in the current produced by the photovoltaic module.

When the current drawn exceeds the current produced by the poorly illuminated cell, the voltage of that cell becomes negative, turning it into a receiving element.

The cell then dissipates an excessive amount of electrical power, which could lead to its destruction if the fault persists for too long. This phenomenon is known as the "hot spot effect".

To address this issue, photovoltaic panels are equipped with bypass diodes, which serve to protect cells that become passive. When the bypass diode activates, it short-circuits a part of the module, thereby preventing reverse currents within defective cells. However, this effective solution reduces both the power output and the voltage across the module terminals.

The degradation of a cell renders the group of cells associated with the defective cell, and protected by the bypass diode, incapable of producing power

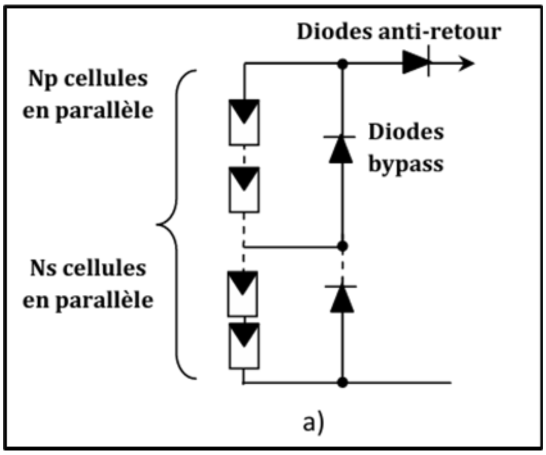


Figure II.4: Classical architecture of a photovoltaic module with protective diodes.

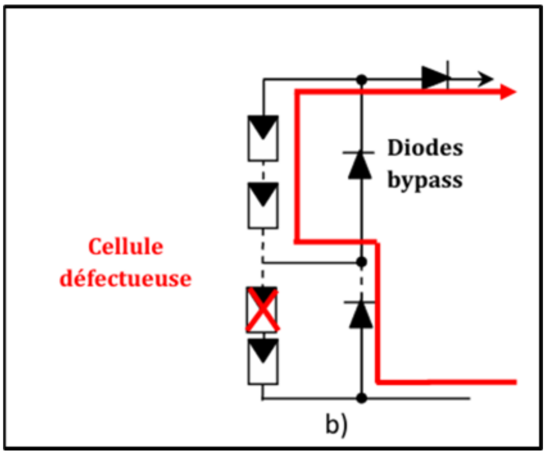


Figure II.4: Failure of one of the PV module cells and activation of the bypass diode, highlighting the circulation current.

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].

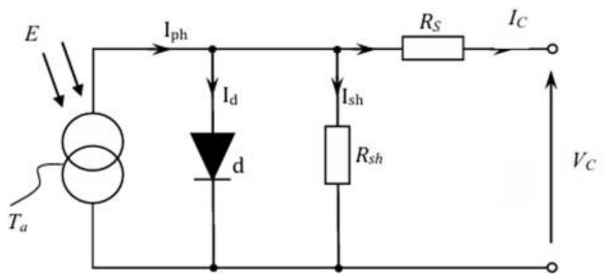


Figure II.5: Equivalent electrical schematic of the PV cell with a single diode.

With:

I_c : Current delivered by the cell.

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

I_d : Current of the diode.

I_{sh} : Shunt current.

$$I_{ph} = P_1 \cdot E_G \cdot \left[1 + P_2 \cdot (E_G - E_{\text{ref}}) + P_3 \cdot \left(T_j - T_{\text{jref}}\right)\right]$$ II.6 II.7

$$T_j = T_a + E_G \left(\frac{N_{oct} - 20}{800}\right)$$ II.8

$$I_d = I_s \left[\exp\left(\frac{q}{A \cdot K \cdot T_j}\left(V_c R_{s-p} \cdot I_c\right)\right) - 1\right]$$ II.9

$$I_s = P_4 \cdot T_j^3 \exp\left(\frac{-E_G}{K \cdot T_j}\right)$$ II.10

II.11

$$I_{sh} = \frac{V_c}{R_{sh}}$$

$$I_c = I_{ph} - I_d - I_{sh}$$

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.

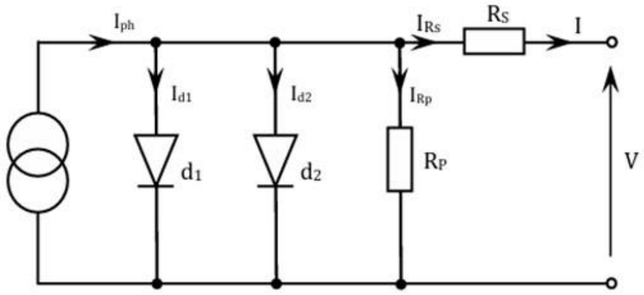


Figure II.6: Electrical two-diode equivalent model of a photovoltaic cell.

$\frac{q(V+IR_S)}{}$ $I_{d1} = I_{s1}\,[e^{\;n_1kT} - 1]$ II.12

Avec:

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

Ainsi :

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

II.14

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

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

$$I_{S1} = K_1T^3e^{\frac{-Eg}{KT}}$$
$$I_{S2} = K_2T^{\frac{5}{2}}e^{\frac{-Eg}{KT}}$$ 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:

$$I = I_{ph} - I_{01}\left[exp\left(\frac{v+R_s}{n_1V_t}\right) - 1\right] - I_{02}\left[exp\left(\frac{v+IR_s}{n_1V_t}\right) - 1\right] - \frac{v+IR_s}{R_p}$$ 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:

$I_P = N_{cp}I_c$ II.18

$V_P = N_{cs}V_c$

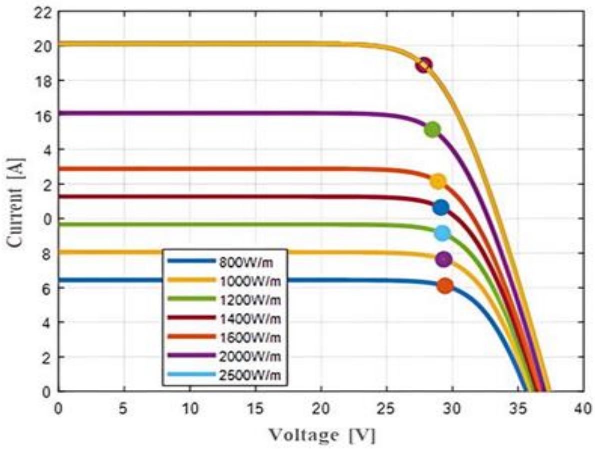
Whereas the current and voltage across the terminals of a photovoltaic generator are given by:

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

$Vg = VPv = NpsVP = NpsNcsVc$

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

❖ **Simulation results**



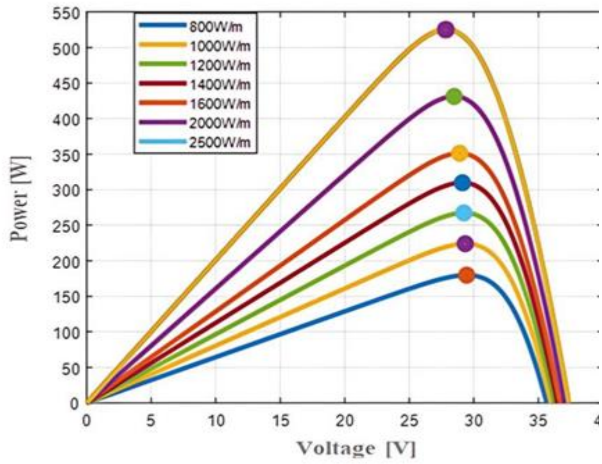
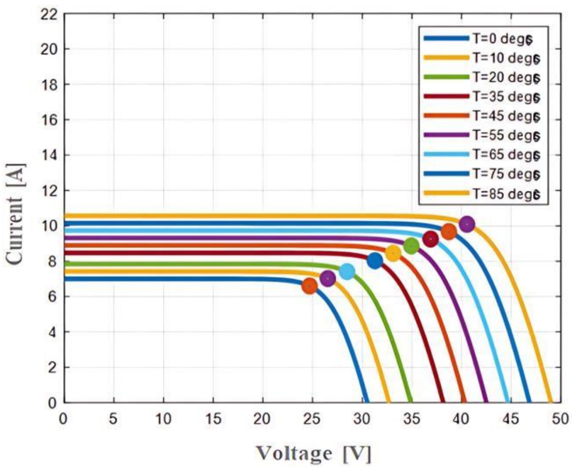


Figure II.7: I-V characteristics, variation of irradiance at constant temperature

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



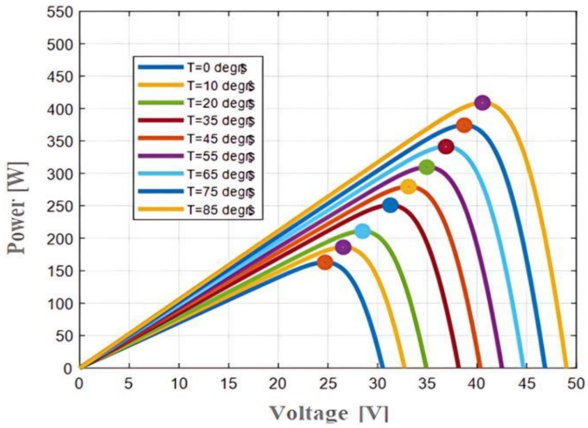


Figure II.9: I-V characteristics, temperature variation at constant solar radiation

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 ($1000w/m^2$) 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^2at 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 illustrate explains the impact of two main environmental factors on the performance of solar panels through two graphs. Figure A shows the effect of humidity on the power-voltage relationship, as the system's power increases with rising voltage until it reaches its maximum point at 13 V and 45 W, then drops sharply due to humidity's effect on the electrical conductivity of components and their corrosion, which reduces efficiency.

Figure B illustrates the effect of dust on the current-voltage relationship, where the current remains constant at first, then gradually decreases followed by a sharp drop at maximum voltage.

This is because dust causes partial shading and light scattering, which reduces the current produced and conversion efficiency.

The text concluded that both humidity and dust lead to reduced energy production and system efficiency, therefore regular maintenance and cleaning are recommended to improve performance..

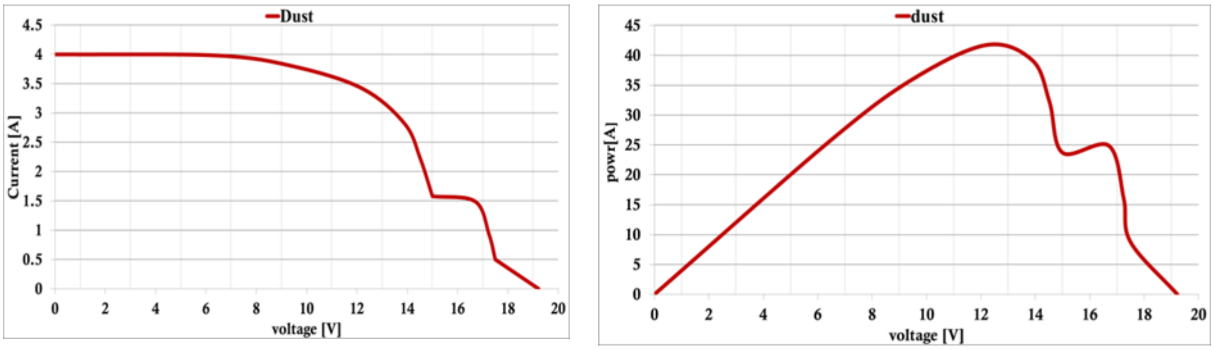


Figure 11: shows the impact of dust accumulation on the PV panels

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

Partial shading is one of the main environmental challenges facing photovoltaic systems, and its impact can be illustrated through two graphs. Figure (A) shows the relationship between electrical power and voltage, displaying nonlinear behavior characterized by the presence of multiple peaks instead of a single peak. This reflects the variation in solar cell performance; while some cells operate efficiently under direct sunlight, others are affected by the shade cast upon them. The multiplicity of peaks leads to the appearance of multiple maximum power points (MPPs), which complicates the task of the Maximum Power Point Tracking (MPPT) system and increases the likelihood of it settling at a suboptimal power point.

Figure (B) depicts the relationship between current and voltage under the same shading effect, where the current remains constant at low voltage and then begins to gradually decrease as voltage increases. Clear breaks appear in the curve as a result of the shading effect, and the different current levels reveal the presence of multiple operating points.

This phenomenon calls for the use of advanced technical solutions such as multi-point MPPT techniques or bypass diodes to mitigate negative effects and improve overall system performance.

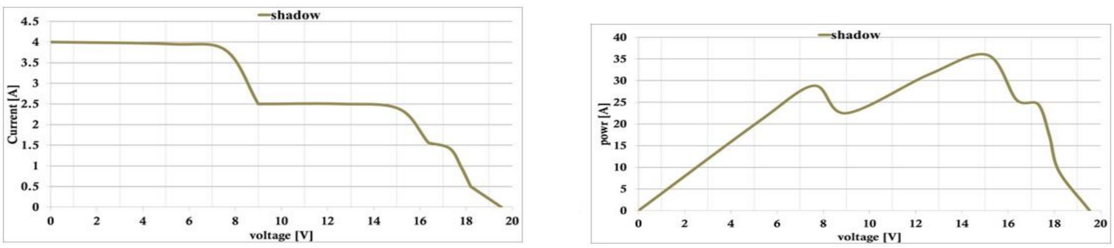


Figure 12: shows the impact of partial shading on the PV panels

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

Humidity significantly affects the performance of photovoltaic systems, and this can be illustrated through two main graphs. Figure (A) depicts the relationship between electrical power and voltage, where power begins to gradually increase with rising voltage until it reaches its peak at about 13.5 volts, which represents the optimal operating point of the system. Beyond this threshold, a sharp decline in power occurs as a result of the negative effect of humidity, which becomes more evident at high voltages.

Figure (B) illustrates the relationship between voltage and current under the same conditions. The current maintains its relative stability at a value of approximately 4 amps in the low voltage region (up to 7 volts), indicating stability in conductivity. As voltage continues to rise, the current begins to gradually decrease due to changes in the electrical properties of the materials and increased resistance caused by humidity. The situation reaches its peak at voltages between 13 and 16 volts, where a sharp drop in current occurs, indicating the onset of system breakdown. This decline continues until the current completely diminishes at 20 volts, meaning a total loss of electrical conductivity as a result of the cumulative effect of both humidity and high voltage.

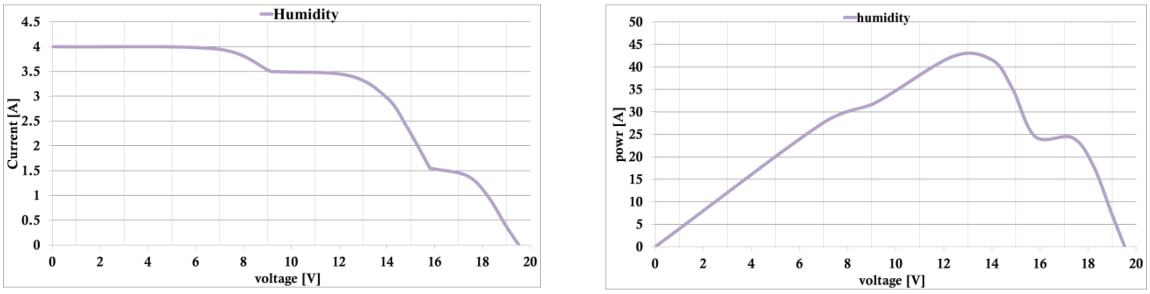


Figure 13: shows the impact of the humidity intensity on the PV system

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 illustrate the behavior of a photovoltaic system under different operating conditions, focusing on the short-circuit condition as one of the important indicators of system health. Figure (A) depicts the relationship between voltage and power, where power begins to gradually increase with rising voltage until it reaches its peak at about 11 volts, which represents the maximum operating efficiency point of the system. Beyond this point, a sharp decline in power occurs due to a short circuit, where a large current flows without a suitable load, causing rapid power loss. This abnormal behavior is a warning indicator of internal faults or damage to system components, necessitating the application of strict protection measures and regular inspections to avoid serious failures.

Figure (B) displays the relationship between current and voltage in a solar cell under normal conditions, where the current starts at a high value reaching approximately 4.2 amps at zero voltage, known as the short-circuit current.

As voltage increases, the current begins to gradually decrease until it approaches zero at about 13 volts, known as the open-circuit voltage. The curve shows a sharp decline in current before reaching zero, and this region represents the maximum power point (MPP), which reflects the optimal performance of the system under ideal lighting conditions. This figure reflects the typical performance of a solar panel and highlights the importance of maximum power point tracking techniques to ensure maximum utilization of available solar energy.

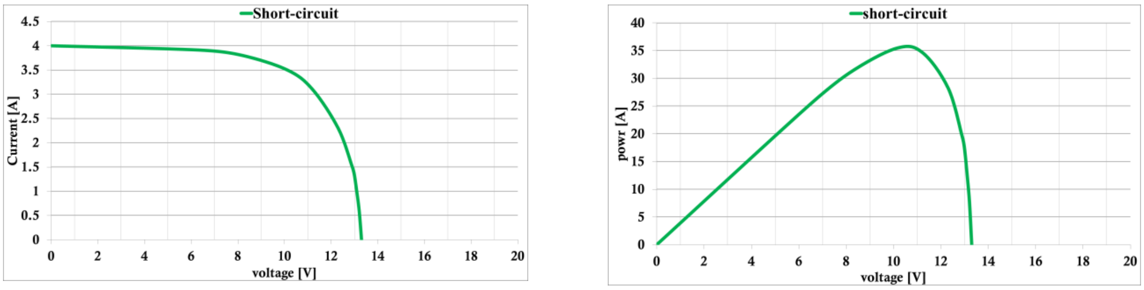


Figure 14: shows the impact of short circuit in PV system.

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 the performance of photovoltaic systems through two main graphs. In Figure (A), which represents the relationship between voltage and power, we observe a gradual increase in power with rising voltage until it reaches its maximum at the maximum power point (MPP), located at approximately 13 volts. Beyond this point, power begins to gradually decrease as voltage continues to rise, reflecting the decline in system efficiency over time due to natural degradation. This degradation is attributed to accumulated environmental factors such as heat, ultraviolet radiation, and humidity, which negatively affect component performance gradually without causing sharp fluctuations in the curve, confirming that this degradation is an internal and natural process.

Figure (B) depicts the relationship between current and voltage, where current starts at a high value and remains relatively constant until approximately 11 volts, then begins to gradually decrease until it completely diminishes at the open-circuit voltage. This behavior reflects the gradual degradation of solar cells caused by thermal expansion and continuous exposure to climatic factors, without the appearance of sharp breaks in the curve. This also indicates the nature of natural degradation, which differs from sudden failures. Based on this, periodic monitoring of these curves becomes an essential tool for determining the annual degradation rate, which helps in applying advanced techniques such as Maximum Power Point Tracking (MPPT) and improving maintenance plans to ensure the continued operational efficiency of the photovoltaic system in the long term.

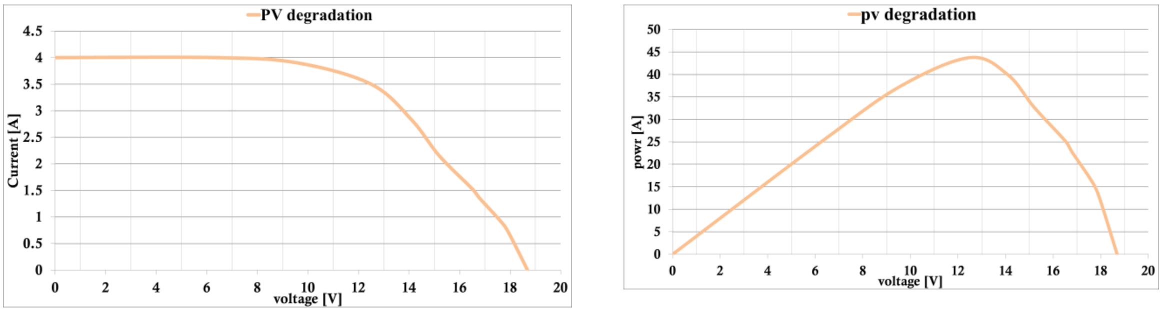


Figure 15: shows the impact of degradation of PV panels with time

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

The study emphasizes the importance of system modeling and analysis of external factors as an essential step for understanding and designing complex systems. Modeling helps simplify reality and predict system behavior, while analyzing external influences helps identify environmental and operational factors that may affect performance. This integrated approach leads to supporting informed decision-making and developing adaptive strategies, ensuring the design of more flexible and efficient systems capable of achieving long-term sustainability.

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CHAPTER III

Test and Application

III.1. Introduction

Health monitoring and fault detection in photovoltaic (PV) systems are essential formaximizing efficiency and lifespan. Deviations in current-voltage (I-V) curves indicatepotential faults, requiring advanced diagnostic methods.

This study presents an AI-enhancedapproach combining optimization and classification for accurate fault analysis.

A DC/DCbuck-boost converter is implemented for real-time I-V dataextraction.

The proposed methodimproves reliability and reduces maintenance costs in PV power plants.

This researchcontributes to smarter, more sustainable solar energymanagement.

III .1.1. Explanation of the applied part

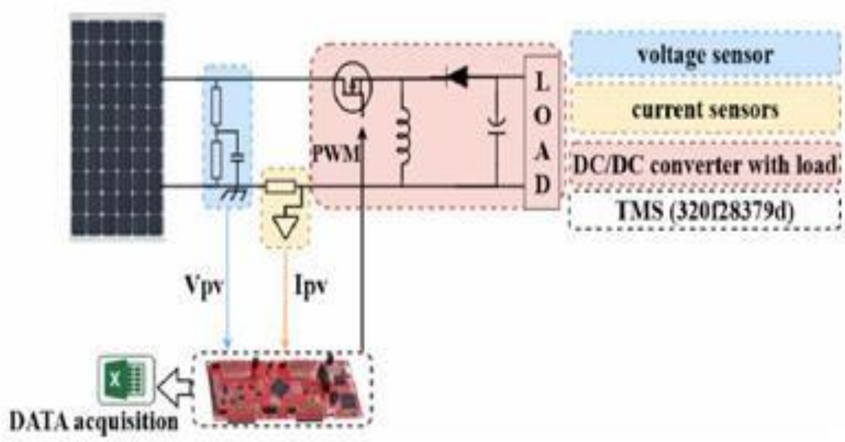


Fig. 1. Proposed Circuit for Extracting Voltage-Current Characteristics Using a DC-DC Buck-Boost Converter.

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-Icurve).

3. Steps for Extracting Electrical Characteristics

- **Power the circuit and stabilize the power supply (e.g., 24 VDC).**

The statement refers to the necessity of supplying the electrical circuit with a specified direct voltage (e.g., 24 VDC) while ensuring power supply stability prior to operation, in order to guarantee component safety, operational accuracy, and the prevention of electrical disturbances that may affect system performance.

- **Gradually change the load (e.g., using a variable resistor).**

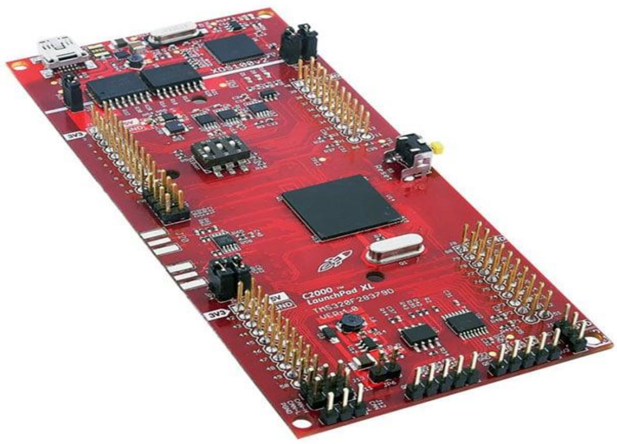
The statement refers to the controlled and progressive adjustment of the electrical load, typically through a variable resistor, in order to evaluate circuit performance under varying operating conditions while preventing sudden stress or instability in the system.

- **Record the Vpv and Ipv values with each load change**.

The statement refers to the systematic measurement and documentation of photovoltaic voltage (Vpv) and current (Ipv) at each load variation, in order to analyze system performance and accurately evaluate its electrical characteristics under different operating conditions.

- **Use the TMS module to adjust the converter's operation and maintain system stability**.

The TMS module is used to regulate the converter’s operation by continuously monitoring key parameters and applying corrective control actions. Through real-time adjustments, it compensates for disturbances and load variations, thereby preventing instability and ensuring reliable, stable, and efficient system performance.



- **Plot the curve using the recorded data:**

Horizontal axis: Current (Ipv).

Vertical axis: Voltage (Vpv).

III .1.2.Experimental Test Bench for Integrating

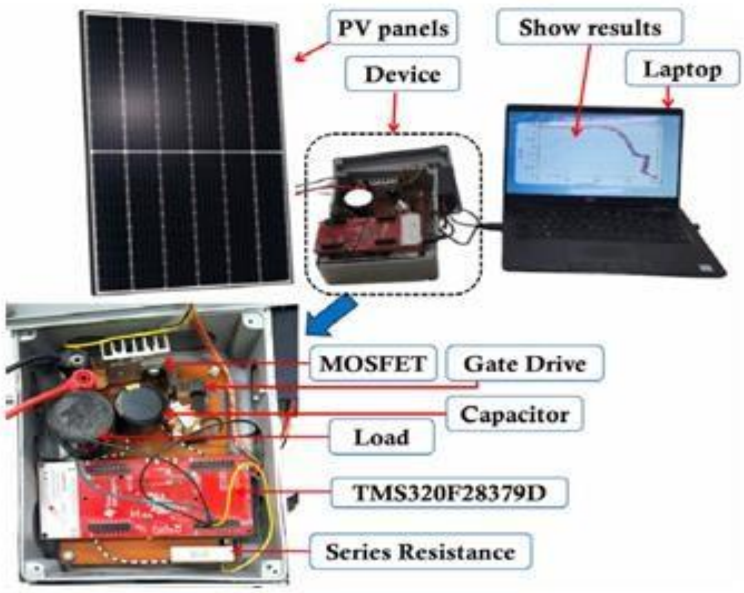


Fig. 5. Experimental Test Bench for Integrating the PV System and Buck-Boost Converte*r* Controlled by the TMS320F28379D LaunchPad.

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.

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 .2.1. Dust

Figures (a) and (b) illustrate the gradual effect of dust accumulation on the electrical characteristics and power performance of the photovoltaic cell.

The current-voltage (I-V) curve shows a clear decrease in the short-circuit current (Isc) as the dust level increases, due to reduced radiation reaching the cell surface and a lower electron-hole pair generation rate. The open-circuit voltage (Voc) remains relatively constant because of its logarithmic dependence on the photocurrent, thus mitigating its impact. A decrease in the fill factor (FF) is also observed due to curve distortion and increased losses. The power-voltage (P-V) curve shows a gradual decrease in the maximum power (Pmax) and a shift in the maximum power point (MPP) towards lower values, reflecting a decline in the overall efficiency of the photovoltaic system. Dust, therefore, acts as an optical loss factor that directly affects the generated current and subsequently the extracted power, highlighting the importance of regular maintenance to maintain stable performance, especially in environments with high concentrations of suspended particles.

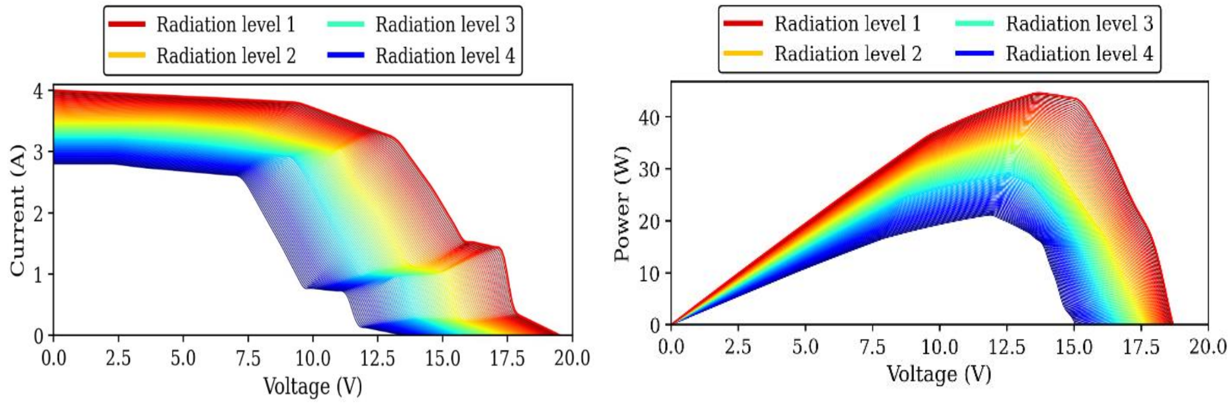


Figure (3.1): The effect of dust on solar panels.

(I-V curve) and (P-V curve)

III .2.2.Shadow

Figures (a) and (b) illustrate the effect of partial shading or reduced solar irradiance on the electrical performance of a photovoltaic cell. In the current-voltage (I-V) curve in Figure (a), a gradual decrease in current is observed at all voltage values as the irradiance level moves from higher (Level 1) to lower (Level 4). This is clearly demonstrated by the decrease in short-circuit current (Isc), which is almost linearly dependent on the incident irradiance. Shading reduces the number of absorbed photons, thus decreasing the generated photocurrent. A relative decrease in open-circuit voltage (Voc) is also recorded, which is expected due to the logarithmic relationship between Voc and photocurrent, reflecting a drop in the peak voltage at lower irradiance levels. Furthermore, the curve becomes steeper and less stable at lower irradiance levels, indicating a decrease in the fill factor (FF) and an increase in the effect of internal losses. The power-voltage (P-V) curve in Figure (b) shows a clear decrease in peak power (Pmax) as irradiance decreases, with the maximum power point (MPP) gradually decreasing and shifting towards lower power and voltage levels. The curve also becomes flatter and more distorted at lower levels, complicating MPPT tracking. These results confirm that shading directly affects photovoltaic current generation and, consequently, the extracted power and overall system efficiency, leading to significant operational losses. This necessitates the adoption of shading compensation techniques and improved power tracking algorithms to ensure optimal performance.

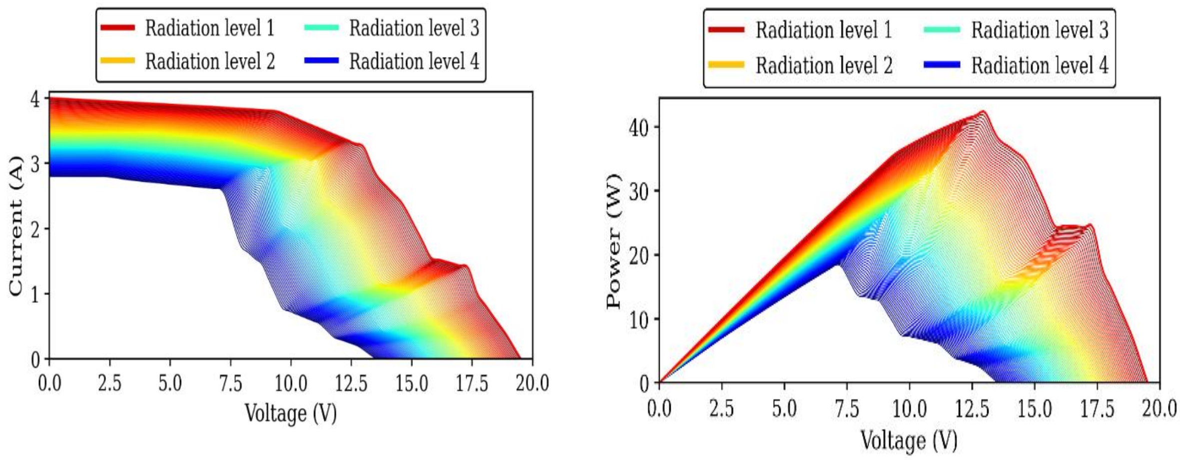


Figure (3.4): The effect of shade on solar panels.

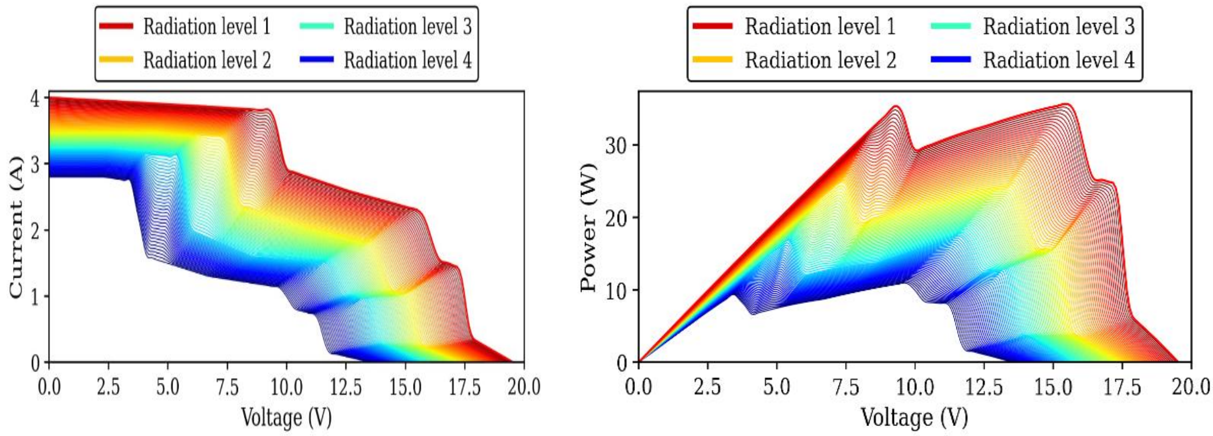
(I-V curve) and (P-V curve)

III .2.3.Humidity

Figures (a) and (b) illustrate the photoelectric effect of high relative humidity on the characteristics of a solar cell at four constant irradiance levels.

In the current-voltage (I-V) curve in Figure (a), a gradual decrease in the short-circuit current (Isc) is observed as humidity increases from level 1 to level 4. This indicates a decrease in the photocurrent generated due to a reduction in the effective irradiance reaching the cell surface. This reduction is caused by the scattering and absorption of a portion of the solar spectrum by water vapor molecules and fine droplets in the surrounding medium. A relative decrease in the open-circuit voltage (Voc) is also recorded. This is explained by the decrease in the photocurrent and the increase in recombination currents within the semiconductor junction, in addition to a possible increase in series resistance (Rs) due to the effect of humidity on the metal contacts and the front surface. Furthermore, a distortion is observed in the knee region of the curve, indicating a decrease in the fill factor and an increase in internal losses.

In the power-voltage (P-V) curve in Figure (b), a more sensitive response to high humidity is observed, with a marked and gradual decrease in peak power (Pmax) and a shift in the maximum power point (MPP) towards lower power and voltage values. This is due to the simultaneous decrease in both current and voltage at the optimum operating region, leading to a decline in the overall energy conversion efficiency (η). The curve also becomes flatter and less steep at high humidity levels, indicating a decrease in the fill factor and an increase in ohmic and optical losses. These results suggest that humidity affects the system through two main mechanisms: an optical mechanism, which reduces transmitted radiation, and an electrical mechanism, which increases internal losses and degrades junction characteristics, ultimately resulting in a significant decrease in extracted power. Therefore, controlling environmental conditions and mitigating the effects of humidity are crucial for maintaining the stable performance of photovoltaic systems, especially in humid or coastal climates.



Figure(3.5): ***The effect of humidity 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.

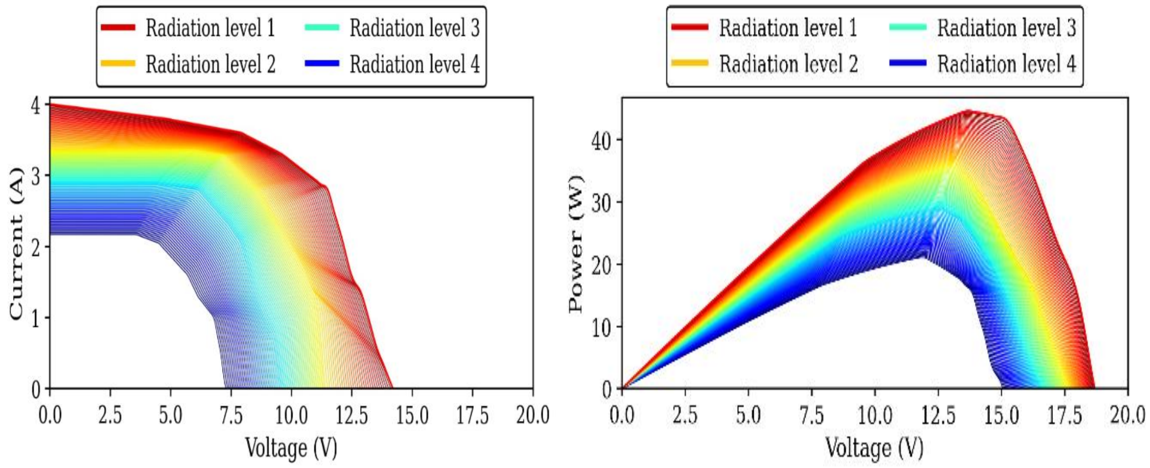


Figure (3.7): The effect of short circuit on solar panels.

(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.

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These analyses are the basis for assessing cell life and improving their maintenance.

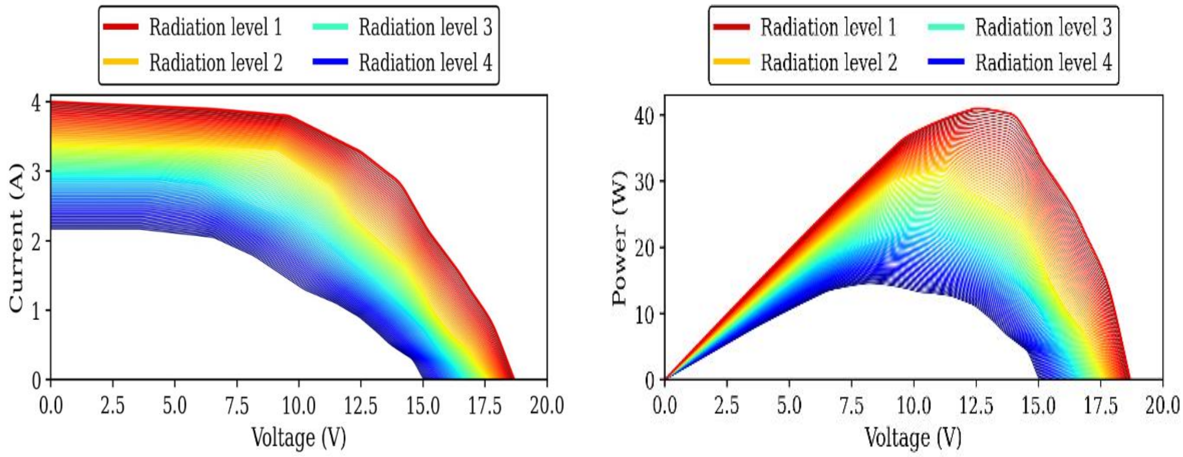

Figure (3.9): Effect of photovoltaic cell degradation

***(I-V curve) and (P-V* curve)**

III .3.Conclusion:

This study underscores the crucial role of advanced diagnostic technologies in enhancing the performance and reliability of photovoltaic systems.

By integrating artificial intelligence techniques with real-time I-V curve data extraction using a Buck-Boost DC/DC converter, the proposed approach enables accurate fault detection and highly efficient system operation.

This integration contributes to reduced maintenance costs, increased solar energy utilization efficiency, and smarter, more sustainable energy resource management, thereby supporting stable performance and maximizing energy yield.

Conclusion générale

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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