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FUZZY LOGIC BASED MAXIMUM POWER POINT TRACKING IN PHOTOVOLTAIC SYSTEM

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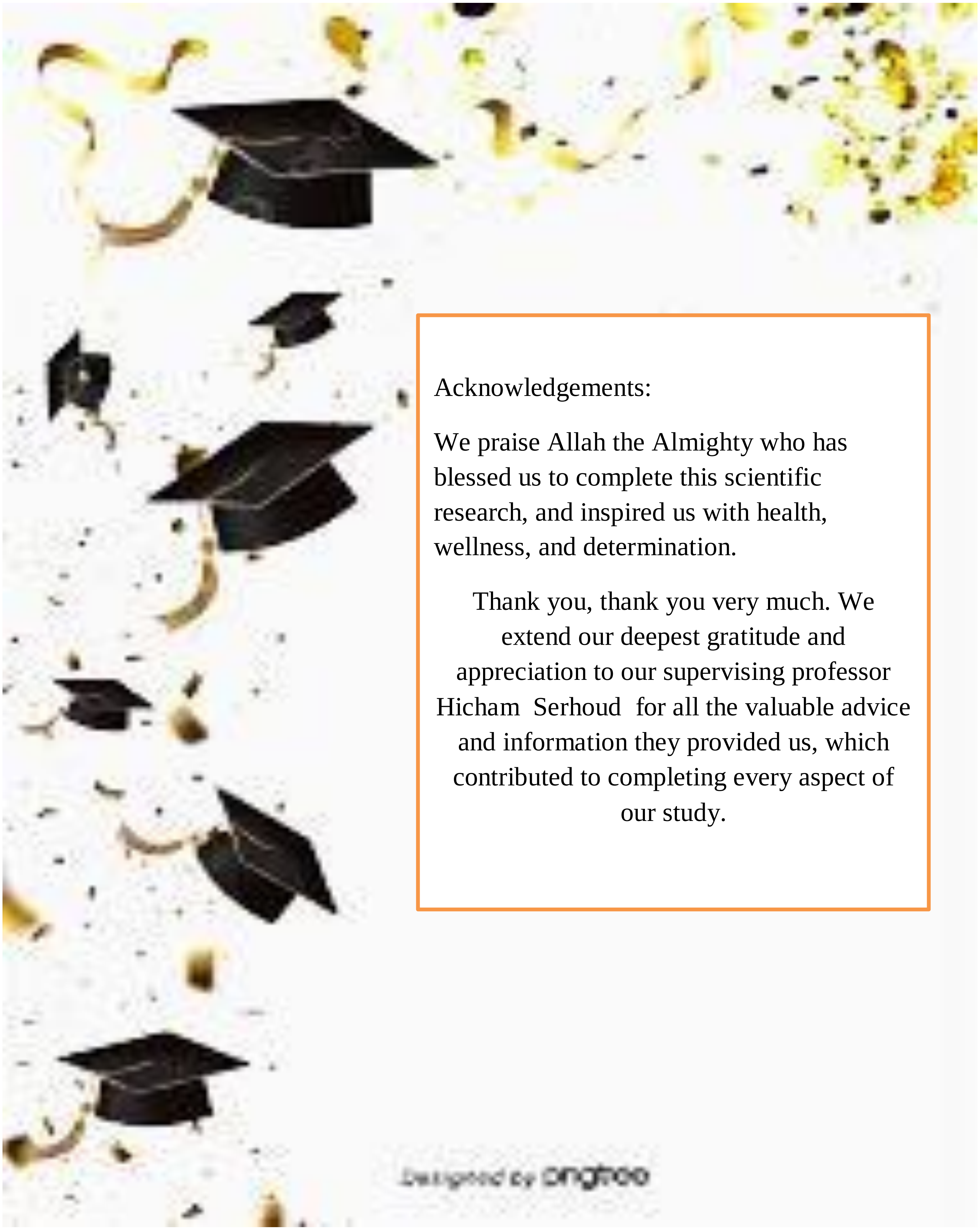

Acknowledgements:

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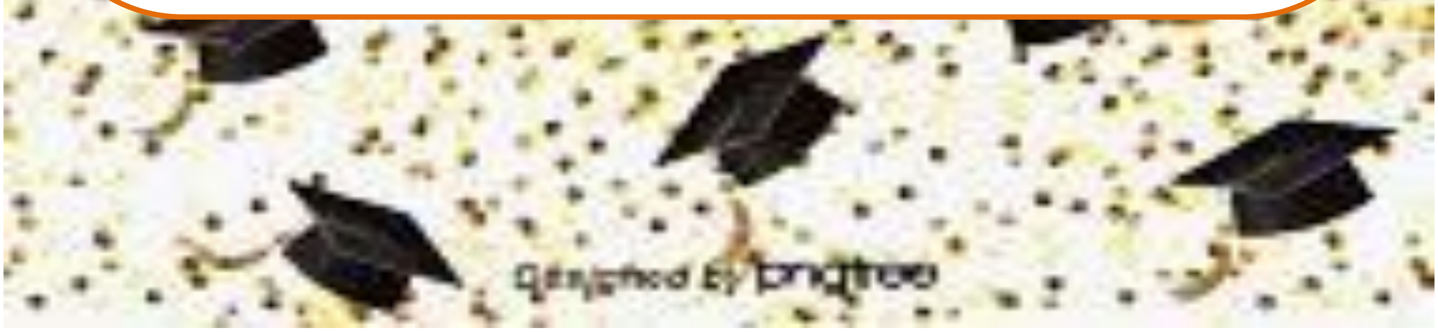
Thank you, thank you very much. We extend our deepest gratitude and appreciation to our supervising professor Hicham Serhoud for all the valuable advice and information they provided us, which contributed to completing every aspect of our study.

Dedication

In the name of Allah, the Most Gracious, the Most Merciful a long journey of successes and failures... Proud of our struggle to achieve our dreams.

A moment I have always awaited and dreamed of, in a story whose chapters have now concluded. To the one who taught me to give without expecting in return, to the one whose name I bear with pride, to the one blessed by Allah with dignity and honor - my beloved father. To the love of my heart, the light of my eyes, and the pulse of my life, to the one whose sincere prayers were the secret of my success - my dearest mother.

To my sisters and brothers, my pillars in life. And to all who stood by us through every moment and every story. To all members of my family and friends without exception. To all the honorable professors who extended their helping hands to us. To them I dedicate this work. May Allah guide me and guide you all to do good.



Abstract

This thesis aims to address the problem of Maximum Power Point Tracking controller (applied to the boost converter of the PV system(able to find the global maximum power point of the non-concave power-voltage characteristic based on the incremental conductance algorithm. The objective of this work is devoted a controller using a fuzzy logic algorithm. The development of membership functions, fuzzy rules employ the Fuzzy Logic toolbox. Both inputs and outputs use triangular membership functions. Simulations results show That This MPPT is effective for using fuzzy controller.

Keywords: Solar power, MPPT, fuzzy algorithm, Incremental conductance

ملخص

تهدف هذه المذكرة إلى معالجة مشكلة تعقب نقطة القدرة العظمى (MPPT) وذلك من خلال تطبيقها على محول الرفع في نظام الطاقة الشمسية. يُستخدم خوارزم التوصيل التدريجي لإيجاد نقطة القدرة العظمى العالمية لمنحنى(الجهد-القدرة)غير المحدب. يركّز هذا العمل على تصميم متحكم يعتمد على خوارزمية المنطق الضبابي. وقد تم تطوير دوال العضوية والقواعد الضبابية باستخدام أدوات المنطق الضبابي، مع اعتماد الدوال المثلثية للمدخلات والمخرجات. أظهرت نتائج المحاكاة أن هذا النظام فعال في استخدام المتحكم الضبابي لتعقب نقطة القدرة العظمى **(MPPT)** .

الكلمات المفتاحية: الطاقة الشمسية، MPPT، خوارزمية ضبابية، التوصيل التدريجي

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PV	Photovoltaic
MPPT	Photovoltaic Maximum power point tracking
DC	Direct current
FLC	Fuzzy logic controller
P&O	Perturb and observe
D	Duty cycle
INC	Incremental conductance

General Introduction:

Most of the energy that people use comes from fossil fuels like coal, oil, and natural gas. But because of overuse, these resources are rapidly running out and represent a major environmental hazard, mostly in the form of pollution and global warming brought on by greenhouse gases. One of the more promising energy sources is renewable energy because it is abundant, pollution-free, and available in different amounts all around the world. Conventional energy sources have become more expensive but also have fewer supplies. Biomass, geothermal energy, wind, tides, and waterfalls are examples of renewable energy sources. They generate little to no waste or pollutants that degrade the environment while in operation, making them the energy sources of the future. Depending on the energy source and useful energy generated, these energies can connect a specific number of technological fields. The photovoltaic energy sector is examined in this thesis. However, this energy's main disadvantages are its relatively low energy efficiency and the generator's still high cost. To address these problems, two strategies are used: increasing energy efficiency through the use of advanced technology in solar cell manufacture and maximizing the generator's power output. The current study examines and contrasts two approaches for maximizing the quantity of power generated by the photovoltaic generator: optimal fuzzy logic and perturbation and observation. To achieve this aim, we have divided our work into three chapters.

The first chapter covers the PV system, its uses, PV cells, how they work, how to connect photovoltaic cells in series and parallel, their current-voltage (I-V) properties, and dc/dc converters. The second chapter provides an introduction to MPPT methods and their application to the Incremental Conductance. Finally, the third chapter offers a maximum PowerPoint using a fuzzy logic algorithm. By comparing the two techniques, fuzzy logic exhibits better behavior from the point of view of speed of search for MPPT and precision at steady state and also proves to be very efficient during a change in climatic condition.

Chapter I:

General Overview of the Photovoltaic System

I.1Introduction:

The sun is an almost limitless energy source, capable of meeting our global energy demand thousands of times over. For this reason, humans have long sought to harness this abundant and widely distributed energy. This goal has been achieved through photovoltaic cells.

Solar energy is abundantly available across the Earth's surface. Even after significant attenuation as it passes through the atmosphere, the remaining energy reaching the ground remains substantial. In temperate zones, it can reach up to 10,000 W/m² under peak conditions, and up to 14,000 W/m² in areas with low atmospheric pollution.

To better understand how this energy works and optimize its use, this chapter provides a brief overview of the photovoltaic effect, photovoltaic cells and their performance, as well as solar photovoltaic systems and their efficiency.

I-2. History and Motivation:

Renewable energy refers to naturally replenished energy sources that regenerate at a rate comparable to their consumption. Solar, wind, geothermal, hydropower, tidal energy, and biomass fall into this category, unlike finite resources such as petroleum and uranium .[2]

- ✓ In 1975, K.W. Ford estimated that solar radiation reaching Earth's surface was 10,000 times greater than global energy demand. Figure I-1 illustrates different methods of converting solar energy into electricity, with photovoltaic (PV) cells emerging as one of the most promising solutions .
- ✓ The development of PV technology began in 1839 when Henri Becquerel observed voltage generation between two electrodes in an electrolyte solution under sunlight. Later, Albert Einstein's work on the photoelectric effect revealed that light behaves not only as a wave but also as discrete energy packets (photons), described by :

$$E = \frac{h_c}{\lambda}$$

Where (h) is Planck's constant, (c) is the speed of light, and (λ) is the wavelength. Shorter wavelengths correspond to higher photon energy—a breakthrough that earned Einstein the Nobel Prize in 1905.

- ✓ In 1954, researchers at Bell Labs (D.M. Chapin, C.S. Fuller, and G.L. Pearson) developd the first 6%-efficient silicon solar cell, marking the birth of modern PV technology. Industrial-scale advancements followed, driven by space programs' need for reliable onboard power and sustained research efforts

I.3 Renewable Energy Resources [3][5] :

The development and utilization of renewable energy have experienced significant growth in recent years. Within the next 20-30 years, sustainable energy systems will rely on the rational use of traditional sources alongside increased adoption of renewables, which currently meet 13% of global demand (with hydropower accounting for 10%). Compared to conventional energy (fossil fuels and nuclear), renewables offer two key advantages: sustainability and reduced environmental impact .

I.3. 1.Solar Energy:

Solar energy is an energy source that depends on the sun. This energy enables electricity generation through photovoltaic panels or solar thermal power plants, using sunlight captured by solar panels.[6]

I.3.1.1. Earth-Sun Motion:

The Earth's rotation around its own axis along the geographic poles connecting the North and South Poles. This motion should not be confused with Earth's revolution, its elliptical orbital movement around the Sun.

The Earth's rotation around its axis is a complex motion whose primary component is a rotation completed on average in 23 hours, 56 minutes, and 4.1 seconds. The rotational axis is inclined to the ecliptic plane by an average of 23°26'; this inclination causes the seasons.

The Earth rotates on its axis while simultaneously orbiting the Sun. It takes one year (365 days) to complete a full revolution around the Sun.

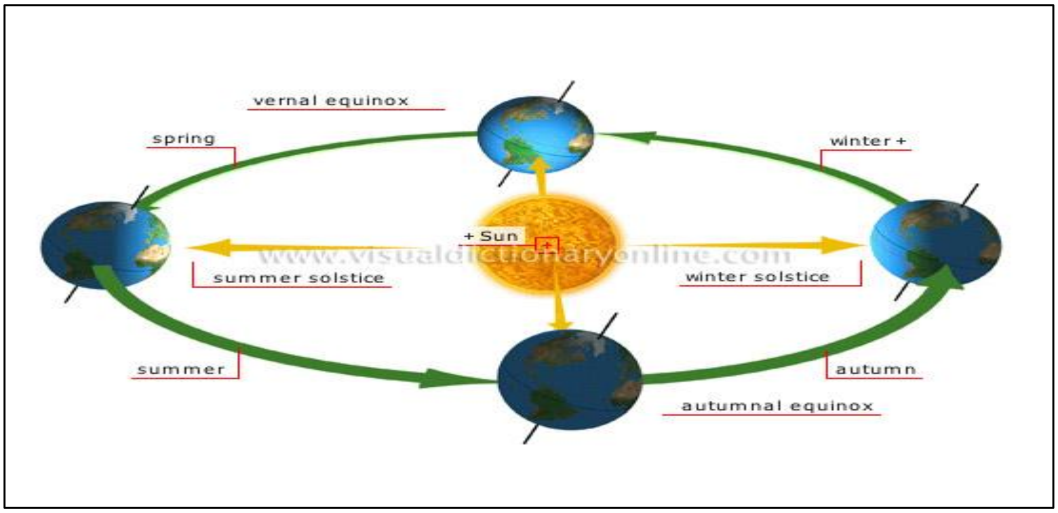


Figure (I.1): Earth's Rotation Around the Sun

1.3.1.2 Solar Radiation [1][2] :

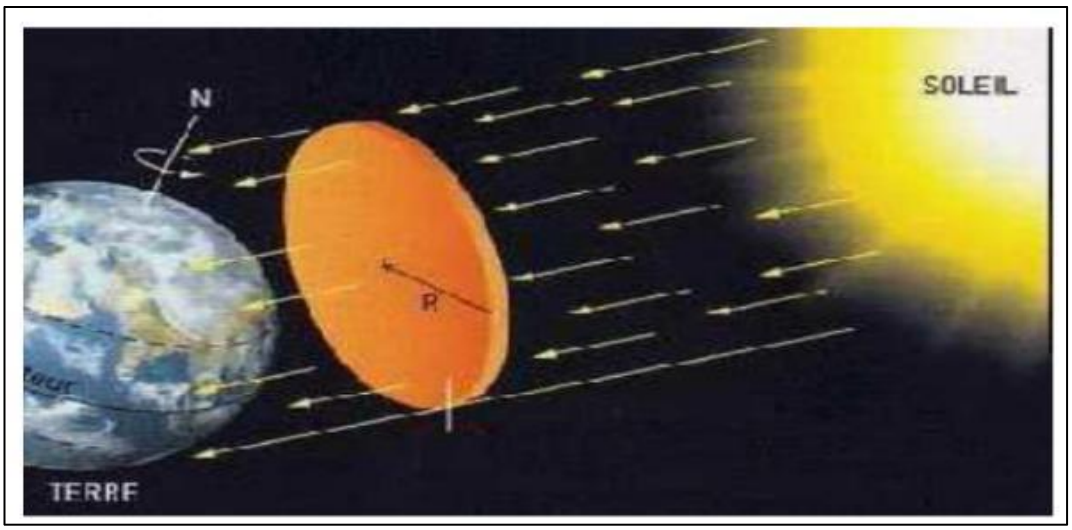


Fig (I.2) : Solar Radiation **.**

Despite the vast Earth-Sun distance (150 million km), our planet receives immense solar energy (180 million GW), positioning solar power as a viable alternative to other energy sources. This energy reaches Earth as electromagnetic radiation with wavelengths ranging from(0.22 to 10 µm), distributed as :

%9 -ultraviolet (<0.4 µm)

%47-visible light (0.4–0.8 µm)

%44 -infrared (>0.8 µm)

I.1.3.3 Types of Solar Radiation [3][4][5]:

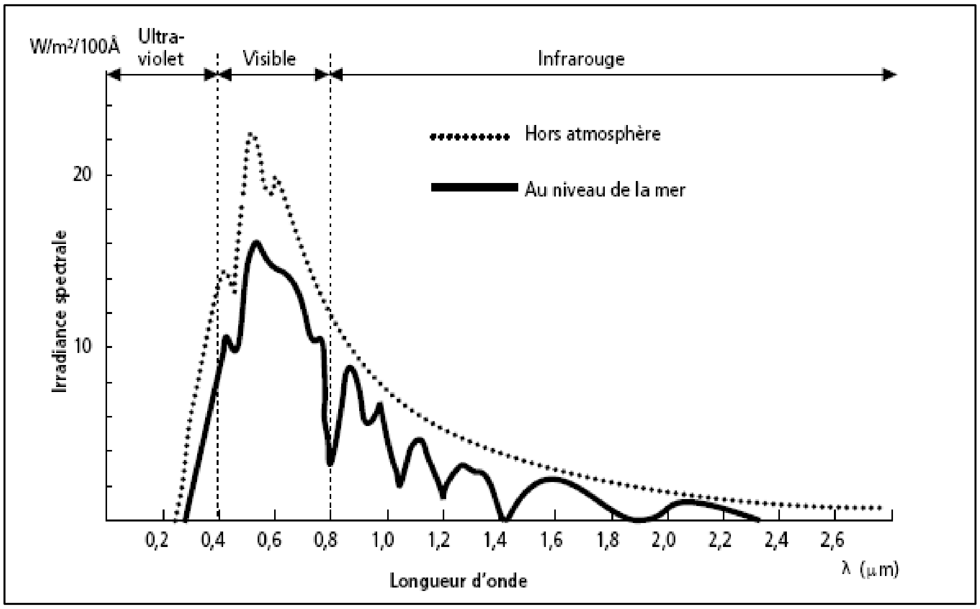


Fig (I.3) : Analyse spectrale du rayonnement solaire.

1. **Direct Radiation:** Travels unimpeded from the Sun, casting shadows and being concentrate able (measured by pyrano meters) .
2. **Diffuse Radiation:** Scattered by atmospheric particles (air, clouds, aerosols), creating ambient light .
3. **Albedo (Reflected Radiation):** Bounced off surfaces (e.g., snow, water), varying with ground reflectivity .
4. **Global Radiation:** The total of all above components, measured by unshielded pyranometers / solari meters.

I.4.The Photovoltaic:

The term "photovoltaic" originates from Greek ("photos" meaning light) and Italian physicist Alessandro Volta's name (inventor of the electric battery in 1800 and namesake of the volt unit) .

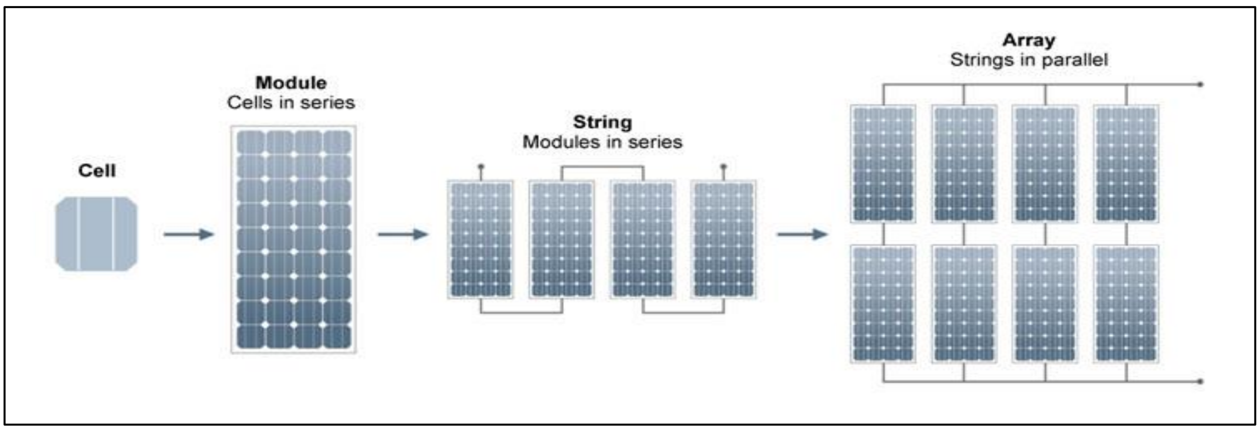
When a semiconductor material is exposed to sunlight, photons bombard its atoms, dislodging valence electrons. While most electrons return to their initial state (converting photon energy into heat), in photovoltaic cells, some electrons remain displaced, generating a weak direct current voltage. This direct conversion of solar radiation into electricity is the photovoltaic effect

First observed in 1839 by French physicist Edmond Becquerel, the effect became practically applicable only in the 1950s when3 Bell Labs researchers developed the first functional silicon photovoltaic cell—the foundational component of modern PV systems. To achieve usable power, multiple cells are interconnected to form solar modules

I.4.1. Photovoltaic System:

A photovoltaic (PV) system is an electrical power supply system primarily consisting of a PV generator, which is made up of one or multiple solar panels.

The basic photovoltaic cell is a very low-power generator, typically around 150 cm² in size, producing approximately 2.3 peak watts (W_p) at about 0.5 volts. This low output is usually insufficient for most domestic or industrial PV applications. To provide adequate voltage and power to external loads, multiple PV cells must be connected in series to form a module. These modules can then be arranged in series and/or parallel to create panels, which are further interconnected to form a PV array (Figure 1.4).



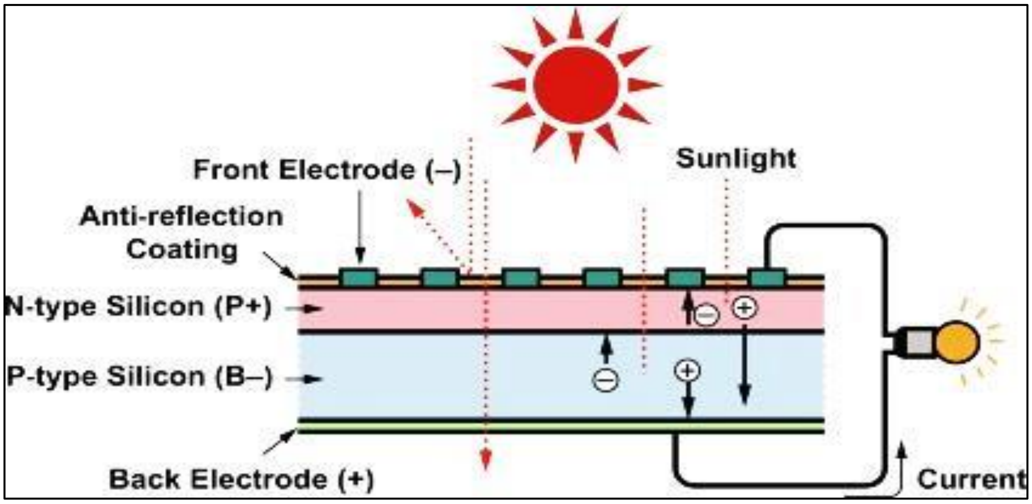
Fig(1.4): PV cell, module, and panel.

I.4.2. The Module (or Panel) :

An individual PV cell—the basic unit of a photovoltaic system—generates only a small amount of electrical power, typically 1 to 3 W with a voltage below 1 V. To increase power output, cells are assembled into a module (or panel). Connecting cells in series raises the voltage while maintaining the same current, whereas parallel connections increase the current while keeping the voltage constant. The peak power output, achieved under maximum sunlight exposure, is proportional to the module's surface area. The front-face rigidity (glass) and the vacuum-sealed back layer ensure the module's durability

I.4.3 Photovoltaic Effect :

PV cell operation relies on the photovoltaic effect [9](Fig.5 shows cross-section)



Fig(I.5): cross-section.

1) **Photon absorption**: in semiconductor layers
2) **Carrier generation**: (electron-hole pairs)
3) **Charge collection**: via doped regions

-N-layer (electron collection) - P-layer (hole collection)

4) **Current extraction**: through top/bottom contacts

I.4.3.1.Photovoltaic Cell Operation:

A PV cell Is constructed from semiconductor material (typically silicon) with a structure similar to a standard diode, comprising two distinct layers :

-N-doped upper layer - P-doped lower layer

- These layers form a PN junction, establishing a potential barrier. When photons strike the cell surface :

1) Energy is transferred to semiconductor atoms
2) Electron-hole pairs are generated
3) A potential difference arises between layers
4) The resulting electric field (E) drives free carriers toward their respective metal contacts

- **This process produces :**

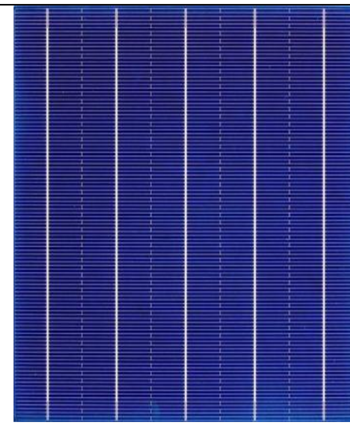
  - Electric current (flow of electrons) - Voltage (potential difference)

- **Output current and voltage vary based on :**

  - Incident light Intensity - Cell material properties - Temperature conditions

Table I.1: Main advantages and disadvantages of different cell categories. [10][7]

Type and definition	Advantage and Disadvantages:	Image
1. Mono crystalline Cells: The solar panels (Mono-SI) are made from high-purity single-crystal silicon. They have a uniform dark appearance with rounded edges and are among the most efficient types, 20% efficiency.	• Very high efficiency. • Most commonly found on the global market. • Sensitive to high temperatures. • High cost.	
2. Polycrystalline Cells: These panels are identifiable by their square shape and blue, speckled appearance. Made by melting silicon, lower efficiency (around 15%)	• Less expensive to produce (cheaper ingots). • Less sensitive to high temperatures. • Lower performance under direct sunlight. • Electronic devices.	
3. Amorphous Cells: These are thin-film solar cells made from non-crystalline silicon. They	• Very thin layers. • Operates well under low light and partial shading.	

have low efficiency (7–10%) but are and they do not contain toxic heavy metals.	• Low efficiency in full sunlight. • Performance decreases over time.	

I.4.3.2. Organic Solar Cells :

An organic photovoltaic cell consists of an organic photosensitive layer (composed of donor (D) and acceptor (A) materials) sandwiched between two electrodes, one of which must be transparent to allow photon penetration into the active layer. When light is absorbed by the active layer, charge carriers are generated and transported within the layer before being collected at the electrodes. In this way, an organic photovoltaic cell converts light into electricity (Figure I.6). [20]

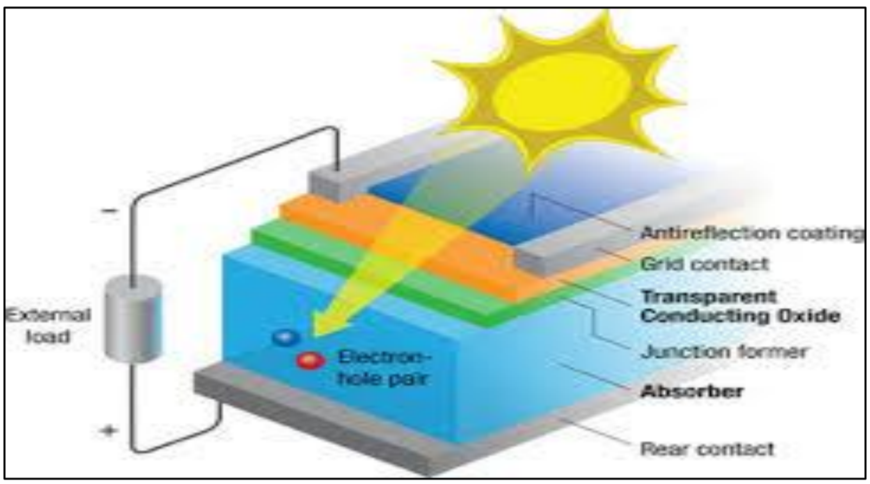


Fig (I.6): Schematic diagram of an organic solar cell.

I.4.4. PV Cell Electricity Generation :

Solar cells transform sunlight into electricity using light-absorbing semiconductors (typically silicon). Photon energy liberates electrons, creating voltage potential. Electron flow between negative and positive contacts generates current when connected in a circuit (see Figure).

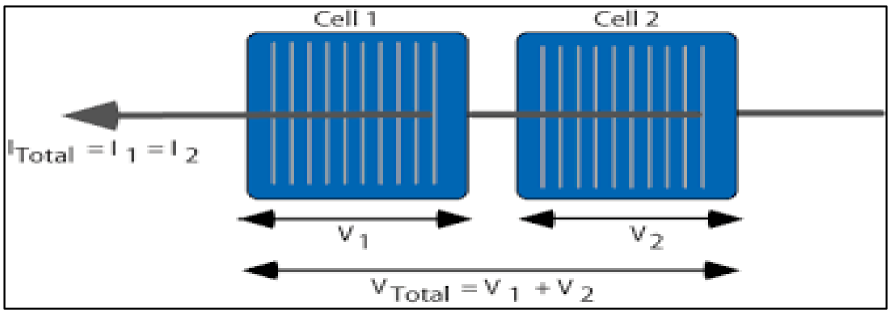
I.4.4.1 PV Cell Electricity Output:

A single photovoltaic cell typically generates 1-2 watts, insufficient for practical applications. Multiple cells are interconnected to form modules, which are combined into panels or arrays to achieve required power outputs. System size scales with energy demands.

I.4.5. Connecting of PV cells:

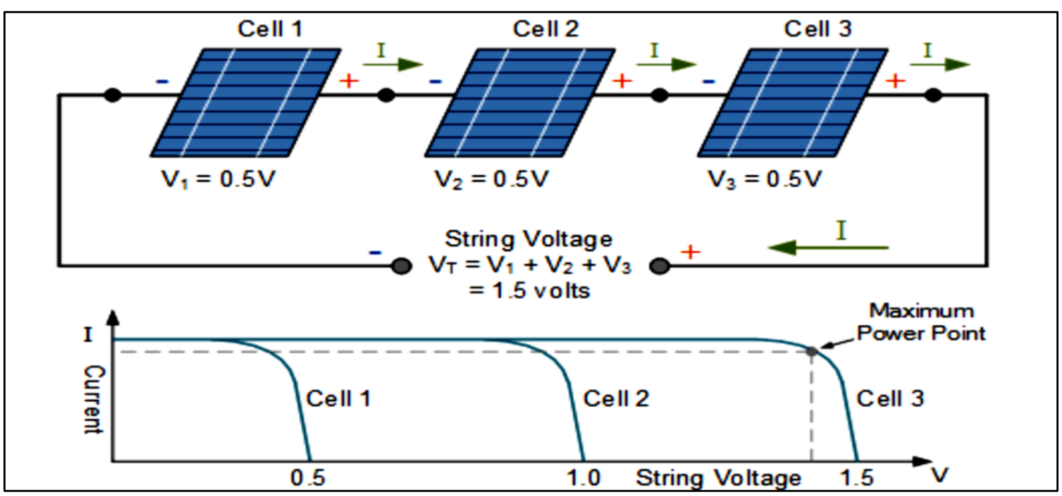
I.4.5.1. Series of photovoltaic cells:

The low operating voltage of a cell (around 0.6 V under 1,000 W/m²) makes it barely usable in practice, requiring multiple cells to be connected in series to increase voltage (fig. I.7)



Fig(I.7): Series photovoltaic cell connection.

When solar cells are connected in series, their voltages add up (N cells provide N times a single cell's voltage), while the current remains constant across all cells. This series configuration's electrical characteristics are shown in Figure I.8[06].



Fig(I.8). Series Connected PV model.

I.4.5.2. Photovoltaic Cell Shading:

Now consider that Solar Cell No.2 in the series string becomes partially or fully shaded while the other two cells remain in full sunlight. In this scenario, the output of the entire series-connected string will decrease significantly, as illustrated [06].

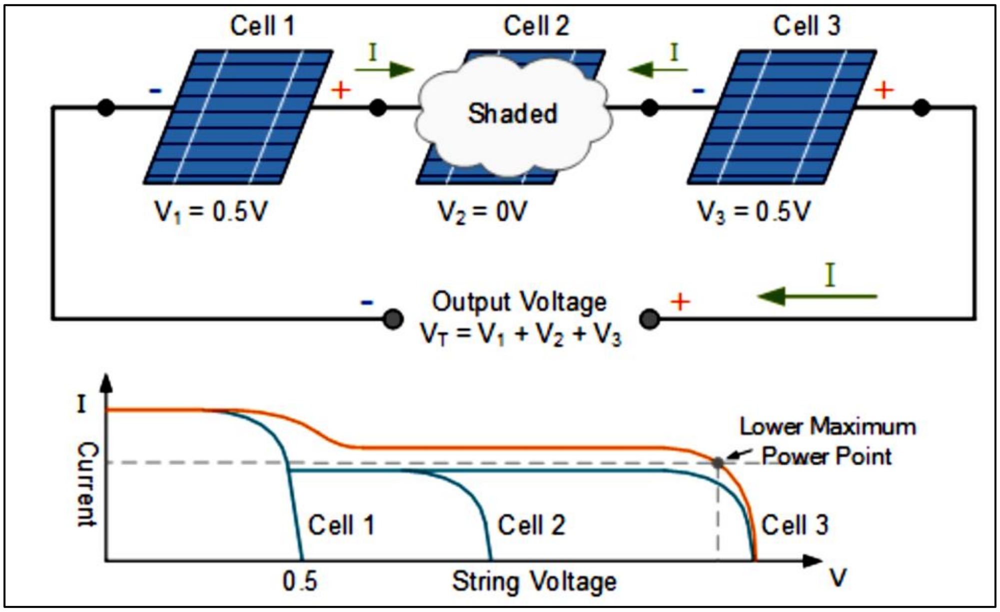
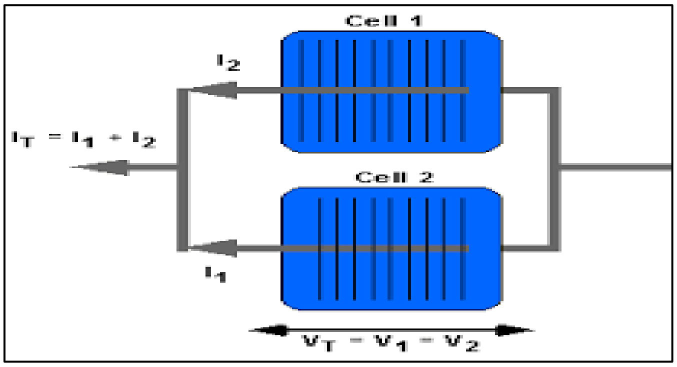


Fig (I.9) series Connected PV Cells.

I.4.5.3. Parallel Photovoltaic Connection:

In parallel configurations, currents sum while voltage remains equal to a single cell's output, thereby increasing the overall current capacity of the photovoltaic system.



Fig(I.10) a parallel photovoltaic cell.

I.5. Converting DC to AC Electricity:

Photovoltaic (PV) cells produce direct current (DC). This DC power requires conversion to alternating current (AC) for use in residential lighting systems and electrical appliances. An inverter performs this DC-to-AC conversion, similar to how batteries' DC output gets converted to AC.

I.6. Generating AC electricity by solar panel photovoltaic system:

A solar photovoltaic panel array generates DC electricity. The conversion from DC to AC is accomplished through a "Solar PV Balance-of-System" (BOS) configuration.

The BOS incorporates several components for DC-to-AC conversion, including:

- Solar panels that produce DC electricity from sunlight
- An inverter for DC-to-AC conversion
- Solar batteries for energy storage
- Various electrical components necessary for system installation and operation

I.7. DC-DC Converters

There are three main types of DC-DC converter circuits: buck, boost, and buck-boost. Each uses a power device as a switch. Initially, thyristors were used, triggered by a gate pulse. They are connected in series with the load and DC supply, and turn off when current drops below holding value or when reverse voltage is applied. Since they require force-commutation, additional circuitry—often using another thyristor—is needed. GTOs (Gate Turn-Off Thyristors) were later introduced, which can be turned off by a negative gate current. GTOs have faster switching times, allowing higher frequencies and smaller filters. Previously, these were called “choppers”: buck as “step-down chopper” and boost as “step-up chopper”, with no buck-boost types used then.

The introduction of BJTs (self-commutated) replaced thyristors in converters. The NPN transistor is turned on with a positive base-emitter current and off by removing the signal. The collector is connected to positive voltage. Today, MOSFETs are used in low-voltage, high-current applications because of their fast switching speeds, allowing high-frequency operation and reduced filter size. These are commonly used in Switched Mode Power Supplies (SMPS). For high-voltage applications, IGBTs are preferred over BJTs due to even faster switching, enabling higher frequency converters. Thus, self-commutated transistors are now widely used in DC-DC converters

PV systems exhibit nonlinear characteristics, causing power output fluctuations with atmospheric changes. The dc-dc converter [8] serves as the optimal device for regulating PV source voltage and current output. Figure (I-11)shows a DC-DC converter schematic. This device modifies DC input voltage (V_{in}) to a different DC output voltage (V_{out}), ideally with minimal efficiency losses. The transistor operates as a switch controlled by signal d(t). As depicted in Figure (I-11), the control signal maintains a high state for duration $T_{on}$and a low state for duration T_{off} [8].

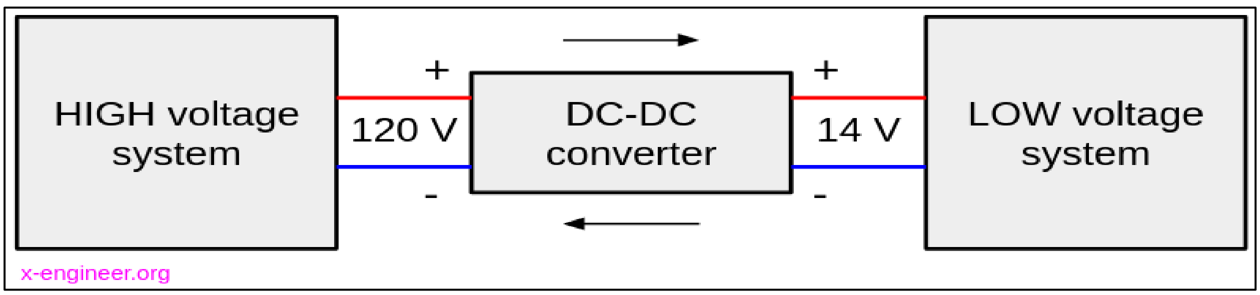


Fig (I.11) structure of a DC-DC converter.

I.7.1. Buck Converters (DC-DC)

A typical buck converter (DC-DC) is shown in Fig (I.12), with a single switch from the transistor family and a freewheeling diode to maintain current flow when the switch is off. The load is inductive (R-L type), and sometimes a battery or back emf is included. Due to the inductance, current path must be provided via the diode; otherwise, the induced emf could damage the switching device. If a thyristor is used, the circuit is termed a step-down chopper, since output voltage is usually lower than input voltage. Hence, the converter is called a buck converter

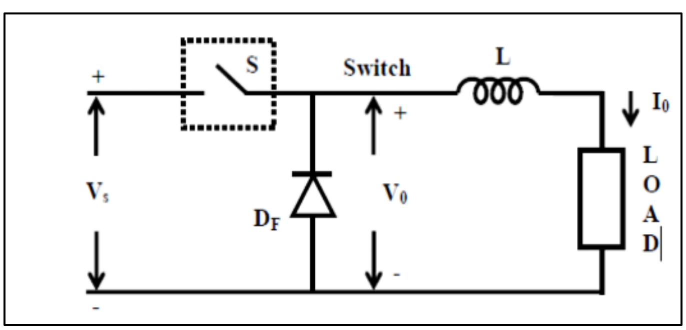


Fig (I.12) Buck Converters (DC-DC)

I.7.2.Boost Converters (DC-DC)

A boost converter (DC-DC) is illustrated in Fig (I.13)Only a switch is shown, for which a device from the transistor family is generally employed. In addition, a diode is placed in series with the load. The load type remains the same as previously described. The inductance in the load is minimal. An inductance, denoted as L, is considered to be in series with the input supply. It is important to note the placement of the switch and the diode in this circuit in comparison to their positions in the buck converter.

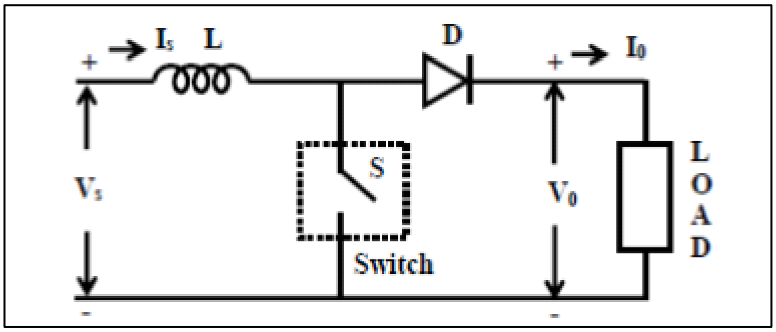


Fig (I.13) Boost Converters (DC-DC)

I.7.3.Buck-Boost Converters (DC-DC)

A buck-boost converter (DC-DC) is illustrated in the figure. It includes only a switch, typically implemented using a device from the transistor family. Additionally, a diode is connected in series with the load. The diode's connection should be observed in comparison with its placement in the boost converter Fig (I.14).An inductor, L, is connected in parallel after the switch and before the diode. The load remains the same type as mentioned earlier. A capacitor, C, is placed in parallel with the load. Notably, the polarity of the output voltage in this configuration is opposite to that of the input voltage.

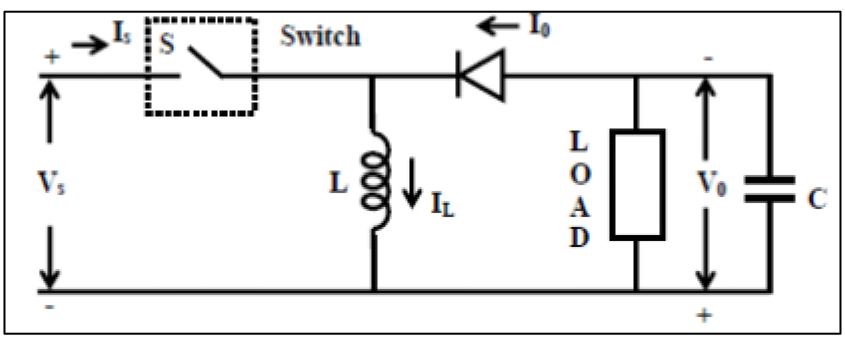


Fig (I.14) Buck-Boost Converters (DC-DC)

I.8. THE INVERTER:

Inverters serve as the control center of solar energy systems. Their primary role involves receiving DC power from either solar panels or batteries and transforming it into usable AC power for household appliances. Essentially, a solar system cannot function without an inverter.

An inverter doesn't generate electrical energy independently; it solely converts energy from DC to AC form. For operation, the inverter must connect to an energy source (typically batteries). Without connection to a battery bank, the inverter remains non-functional.[06]

I.8.1. There are Inverters and there are Inverter/chargers:

Inverters: Their sole function is converting DC power from batteries to AC power for appliances and devices. They lack built-in charging capability to recharge batteries from an AC power source.

Inverter/chargers: These perform DC-to-AC conversion while also incorporating built-in chargers. The integrated chargers allow battery charging from AC sources (utility power or generators).

Inverter/chargers prove especially valuable for grid-connected solar systems, offering dual charging options:

1. Solar panel charging . 2. Utility/generator charging.

I.8.2. Inverter ratings:

Inverters feature standardized ratings such as: 1.5kW 12V ,2.5kW 24V ,6kW 24V/48V

The ratings are explained through two key parameters:

1. Power capacity . 2. Voltage compatibility.

- **Power (kW)**

1.5kW 12V. This specifies the maximum power capacity of your system is 1.5kW (Note: 1.5kW equals 1500 watts, where 1kW=1000 watts; kW=kilowatts). If your system delivers power exceeding your inverter's capacity (for example 2kW to a 1.5kW inverter), not only would the extra 500 watts be wasted, but the excessive power could potentially damage your inverter without proper precautions.

• Voltage (V)

2.5kW 24V. This indicates your inverter operates with a 24V system. The voltage rating of the inverter you purchase must match your solar system's voltage configuration. It is absolutely critical that you do not select an inverter with different voltage specifications than your system requires. Your system voltage is determined by both your battery bank voltage and your solar panel array voltage. Some advanced inverters can accommodate multiple voltage configurations, such as 7kW 24V/48V systems.

I.8.3. INVERTER (TYPES):

I.8.3.1. String Inverter:

This inverter type, also called central inverter, remains the most commonly used configuration. It consists of a single central inverter unit that connects to all solar panels in the system. All DC power generated by the solar panels feeds into this central inverter, which then converts the combined DC power to AC power for system use.

I.8.3.2. Micro Inverters:

Representing relatively newer technology, micro inverters offer significantly higher efficiency compared to central inverters. These compact inverters install directly on each individual solar panel in the system. They perform DC-to-AC conversion right at the panel level and deliver the converted AC power directly into the system.

I.8.3.3. Power Optimizers:

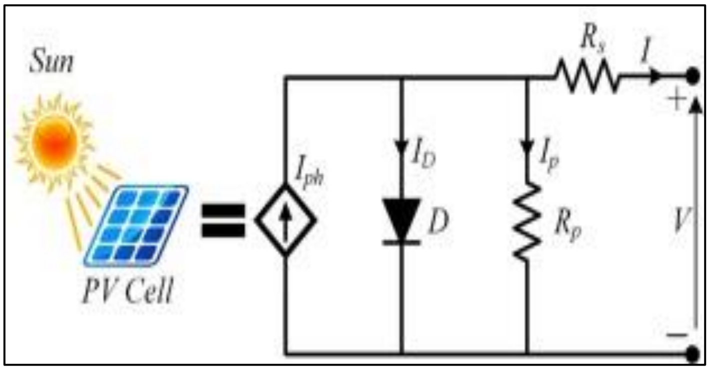
This type serves as an intermediate solution between central inverters and micro inverters. The power optimizers mount on the solar panels like micro inverters, but rather than performing full DC-to-AC conversion, they condition and optimize the DC output from each panel before sending it to a central inverter for final conversion to AC power.

I.9. Photovoltaic Cell Modeling:

I.9.1. Single Diode Model:

Also known as the R_p-Model, this approach accounts for both voltage losses (represented by series resistance R_s) and current leakage (represented by parallel resistance R_p) .

This model serves as the foundation for manufacturers when specifying the technical characteristics of their solar cells (as shown in datasheets). It is widely regarded as satisfactory and has become the standard reference for classifying solar modules. [11]The following figure illustrates the single diode model

:

Fig(I.15): Equivalent Single diode model .

.The output current of the photovoltaic cell is described by:

$$I = I_{PV} - I_0\left(\exp\left(\frac{V + R_S}{AV_T}\right) - 1\right) - \left(\frac{V + IR_S}{R_P}\right) \qquad (I.1)$$

Where

(R_P): Shunt resistance modeling junction leakage (I_0): Diode reverse saturation current

(V_T): Diode thermal voltage (A): Diode ideality factor

I.9.2. Two-Diode Model:

The PV cell's real behavior is modeled using two diodes (D_1 and D_2) as shown in Figure (I.16)

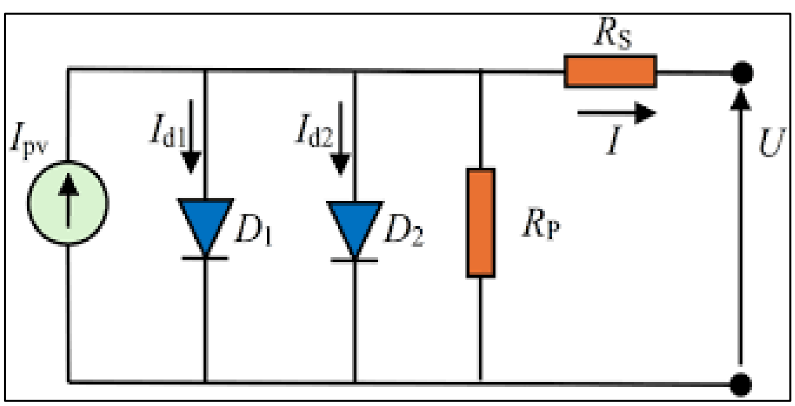


Fig (I.16): Equivalent dual-diode solar cell circuit.

While the single-diode model performs adequately under normal conditions, it shows limitations under low irradiance. Researchers address charge carrier recombination losses in the depletion region by adding a second diode [12] .

$$I_{PV} = I_{Ph} - I_{d1} - I_{d2} - I_P \qquad (I.2)$$

❖ **The solar cell output current is** :

$$I_{PV} = I_{Ph} - I_{01}\left(-1 + \exp\left(\frac{P_{PV} + R_S I_{PV}}{A_1 V_{t1}}\right)\right) - I_{02}\left(-1 + \exp\left(\frac{P_{PV} + R_S I_{PV}}{A_2 V_{t2}}\right)\right) - \left(\frac{P_{PV} + R_S I_{PV}}{R_p}\right) \qquad (I.3)$$

Where :

$(I_{01};\ I_{02})$: Saturation currents of D_1 and D_2

$(A_1\ ;\ A_2)$: Ideality factors

$(V_{t1};\ V_{t2})$: Thermal voltages

❖ **Thermal voltage is defined as** :

$$V_t = V_{t1} = V_{t2} = N_S \frac{K.T}{q} \qquad (I.4)$$

❖ **Diode saturation current** :

$$I_0 = I_{rs}\left(\frac{T}{T_n}\right)^{\frac{3}{A}}.\exp\left(\frac{q.E_g}{A.K}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right) \qquad (I.5)$$

❖ **Reference current** :

$$I_{rs} = \frac{I_{sc}}{-1 + P\left(\frac{V_{oc}}{A.V_t}\right)} \qquad (I.6)$$

I.10. Photovoltaic Module Characteristics

I.10.1. Open-Circuit Voltage (V_{oc}):

The voltage when PV generator current is zero (maximum PV cell voltage). Derived from:

$$0 = I_{ph} - I_{sat}.\left[\exp\left(\frac{V_{co}}{V_t}\right) - 1\right] - \frac{V_{co}}{R_P} \qquad (I.7)$$

For silicon cells, V_{oc} typically ranges 0.55-0.6 V. Ideal case approximation[13]:

$$V_{CO} = \frac{n.K.T}{q}.\ln\left(\frac{I_{CC} + I_{Sat}\,(T)}{I_{Sat}\,(T)}\right) = V_t.\ln\left(1 + \frac{I_{CC}}{I_{Sat}\,(T)}\right) \qquad (I.8)$$

I.10.2. Short-Circuit Current (I_{CC}):

Current delivered at zero resistance[13]:

$$I_{cc} = \frac{R_P}{R_S + R_P}\left(I_S\left(\exp\left(-\frac{qIR_s}{nKT}\right) - 1\right) - I_{ph}\right) \qquad (I.9)$$

I.10.3. Maximum Power (P_{max}):

Obtained by optimizing current-voltage product[24] : $P_m = V_m \times I_m$:

$$\frac{I_m}{V_m} = -\left(\frac{dI_{PV}}{dV_p}\right)_M \qquad (I.10)$$

I.10.4. Fill Factor (FF):

Quality indicator of I-V curve shape:

$$FF = \frac{P_{max}}{V_{co} I_{cc}} \;\; ; avec \;\; P_{max} = V_{max}.I_{max} \qquad (I.11)$$

Ranges 0.25-1, [14] comparing real vs ideal cells ($P_{max} = V_{co}.I_{cc}$) .

I.10.5. Efficiency (η):

Power conversion ratio[15]:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{FF \times V_{co} \times I_{cc}}{P_{in}} \qquad (I.12)$$

Improvement methods: Increase FF I_{cc} *or* V_{co}.

Where *IMPP* is the current at MPP and *VMPP* is the voltage at MPP. The fill factor ranges from material to material and it can be seen that it is always < 1. The closer the fill factor is to unity the better the operation of PV cell. The factors which affect (*FF*) are the shunt and series resistances of the photovoltaic generator as shown above in Fig. (I.17) A good fill factor is between (0.6-0.8) .

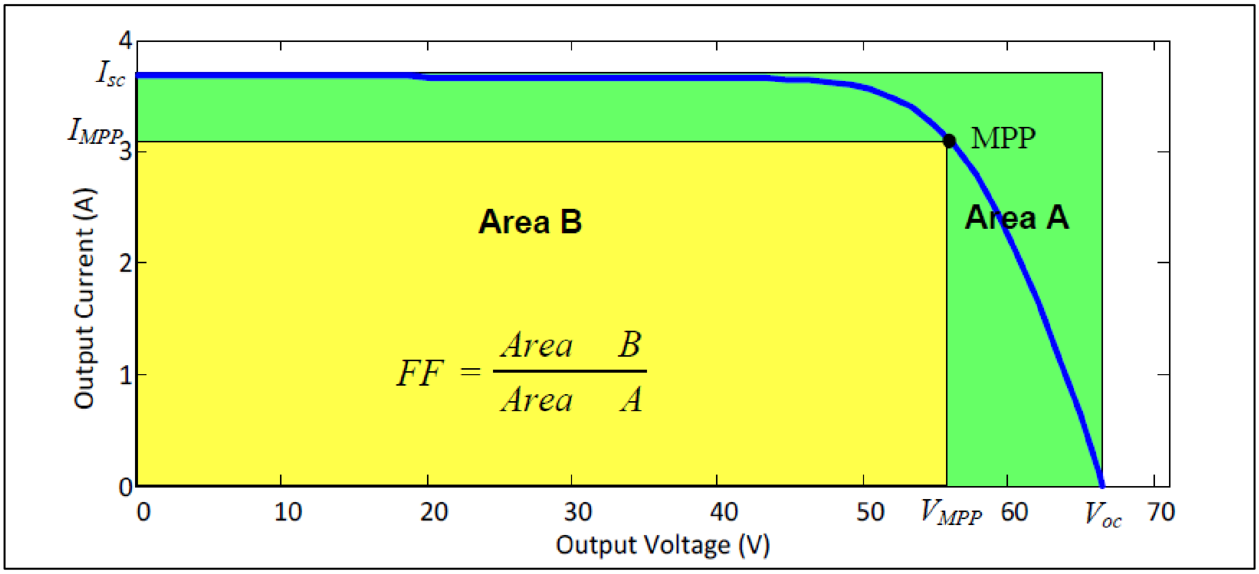


Fig.(I.17): Photovoltaic module characteristics showing the fill factor**.**

I.10.6. Effect of temperature:

The panel temperature is considered one of the important parameters due to its effect on the output power of photovoltaic panel .

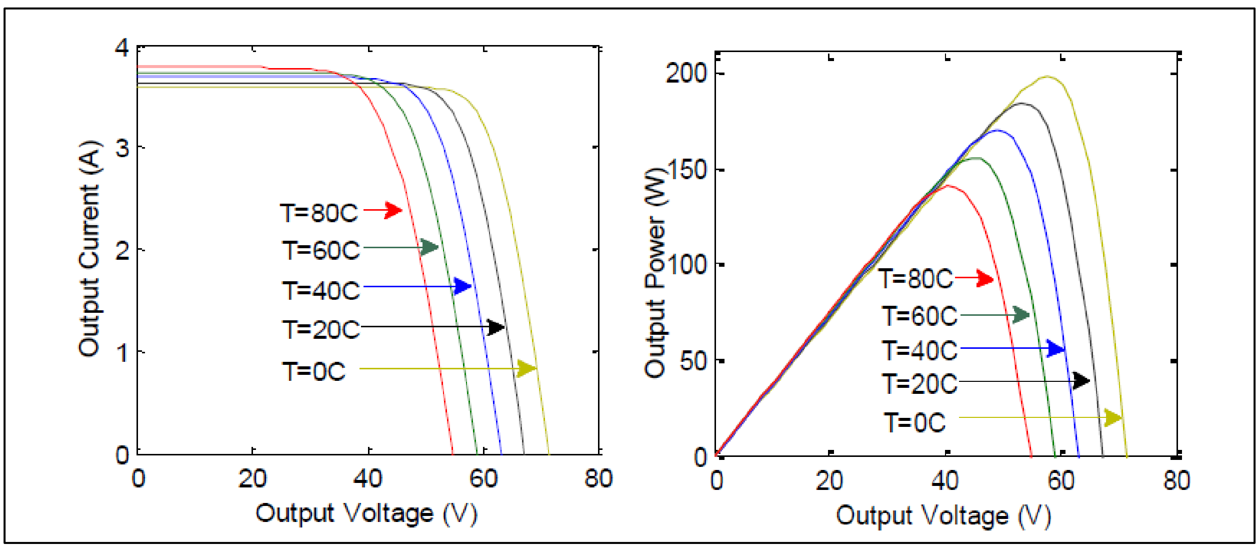


Fig. (I.18): Effect of temperature on the I-V and P-V characteristic at constant irradiance.

The open circuit voltage *VOC* is highly influenced by the increase in the panel temperature as shown in the Fig I.18. As the temperature increases with a fixed irradiation level it results in a slight increase in the short circuit current *ISC*, because the band gap energy decreases and more photons have enough energy to create electron-hole pairs. On the other hand, the increase of temperature have an obvious reduction in the PV panel output power due to the drop in the open circuit voltage *VOC* and the fill factor; therefore the module efficiency is reduced .

I.10.7. Effect of irradiation :

At constant temperature the change in irradiation has a clear effect on the PV output maximum power as illustrated. It is obvious that as the irradiation level increases the PV output voltage and current increases with it. In general, the increment in the irradiation level leads to a theoretical increment in the maximum power voltage when there is no change in the cell temperature. On the other hand, the short circuit current *ISC* depends totally and linearly on the irradiance level; therefore the maximum power current is changed .

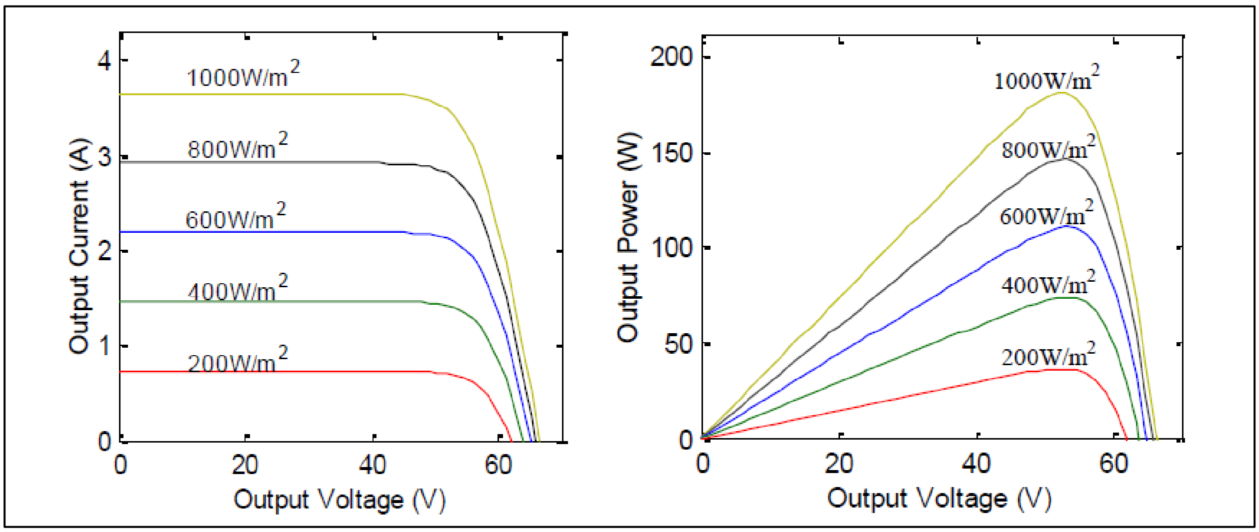


Fig. (I.19): Effect of irradiance on the I-V and P-V characteristic at constant temperature.

I.11 Modeling of a Photovoltaic Cell:

I.11.1 Ideal Photovoltaic Cell [16] :

An ideal PV cell can be represented as:

-A current source generating photocurrent $I = I_{Ph} - I_d$ (proportional to incident light)

-Parallel with a diode representing the P-N junction

Key equations:

- Node current :

$$I = I_{Ph} - I_d \qquad (I.13)$$

- Diode characteristic :

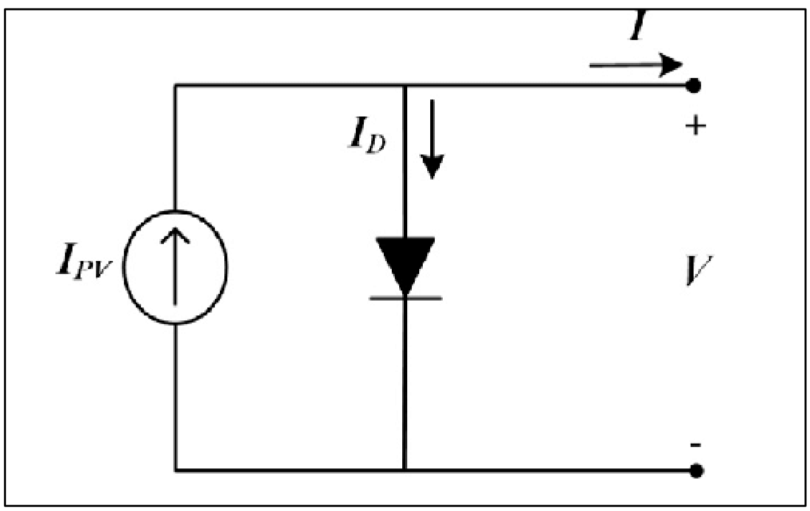
$$I_d = I_0.\left[\exp\left(\frac{V_d}{V_t}\right) - 1\right] \qquad (I.14)$$

Where :

- I_0 : Diode reverse saturation current
- $V_t = \frac{KT}{q}$: Thermal voltage (≈26mV at 300K)

- Combined equation

$$I = I_{ph} - I_0.\left[\exp\left(\frac{V_d}{V_t}\right) - 1\right] \qquad (I.15)$$

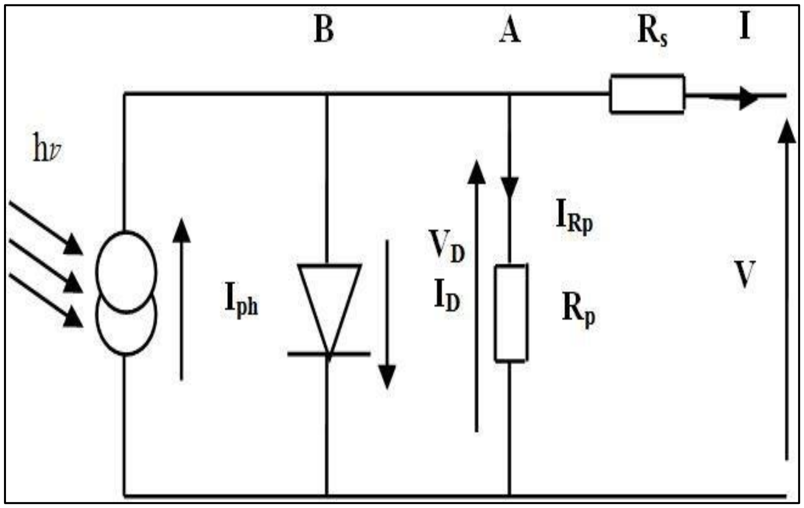


Fig(I.20): Ideal PV cell model .

I.11.2 Real Photovoltaic Cell[17]:

Practical PV cells require additional components to account for

- Series resistance (R_s): Voltage drop at terminals.
- Shunt resistance (R_P): Current leakage paths.



Fig(I.21): Real PV cell model.

Key improvements over ideal model:

- More accurate under varying operating conditions
- Accounts for manufacturing imperfections
- Enables precise performance prediction

➢ **Photovoltaic Cell Current Modeling:**

✓ **Current Components:**

I: Output current of the cell I_{Ph} :Photovoltaic current (light-generated)

I_d:Diode current I_p: Leakage current R_s: Series resistance (thermal losses)

R_p: Parallel/shunt resistance (leakage path)

✓ **Fundamental Equations:**

Applying Kirchhoff's current law:

$$I = I_{ph} - I_p - I_d \qquad (I.16)$$

Where:

✓ Leakage current : $$I_d = \frac{V+IR_S}{R_p} \qquad (I.17)$$

✓ Diode current : $$I_P = I_0\left(exp\frac{q(V+IR_S)}{njKT} - 1\right) \qquad (I.18)$$

with : $V_t = \frac{KT}{q}$ as thermal voltage

Complete Current Equation:

$$I = I_{ph}\frac{E_s}{1000} + \alpha_p\left(T - T_{ref}\right) - I_0\left(exp\frac{q(V + IR_{s})}{njKT} - 1\right) - \frac{V + IR_s}{R_p} \qquad (I.19)$$

Parameters:

Symbol	Description	Units
E_s	Solar irradiance	W/m²
α_p	Temperature coefficient	A/°C
K	Boltzmann constant	J/K
N	Ideality factor	
T	Cell temperature	K
T_{ref}	Reference temperature	K
Q	Electron charge	C

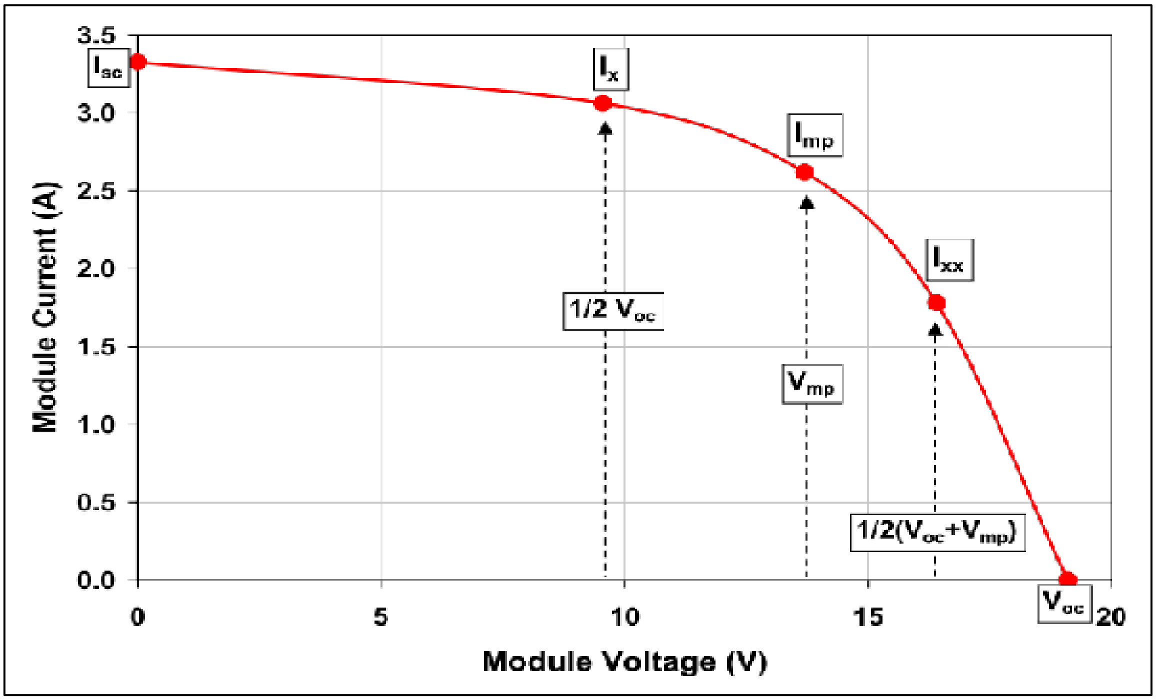
Key Observations:

- Output current is directly proportional to irradiance
- Output current is inversely proportional to temperature
- Series resistance affects voltage drop
- Shunt resistance impacts leakage current

I.12. Characteristic Analysis $I = f(v)$

The electric current provided by the photovoltaic cell as a function of voltage is represented by the following curve

:



Fig(I.22): Characteristic zones of PV I-V curve

From the I = f(V) characteristic in Figure (22), we observe three key points (1), (2), and (3) that essentially define the curve. The characteristic is divided into three parts:

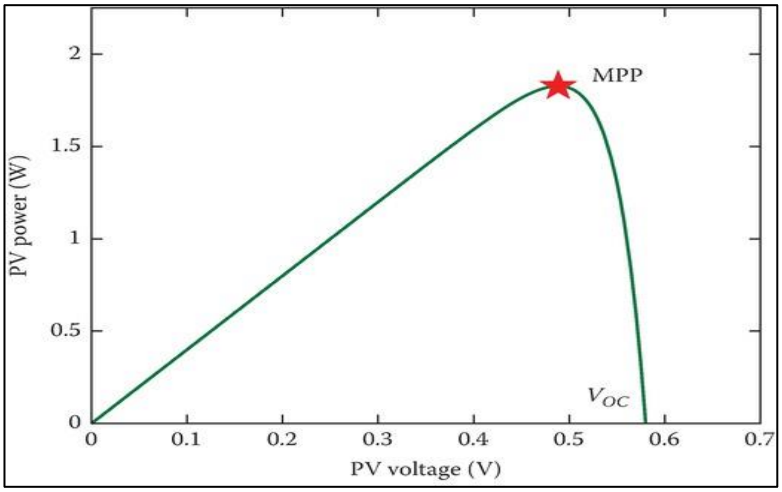
✓ **Zone (1)** where the cell behaves as a current generator producing I_{cc} proportional to illumination, with $U_a = 0$, hence $P_a = 0$.

✓ **Zone (3)** where the cell acts as a voltage generator producing V_{co}, with $I_{cc} = 0$, Ue max. $P_c = 0$.

✓ All other points on the curve correspond to specific power values, but there exists one point where the power is maximum, corresponding to zone (2).

I.13.The Power chaeacteristic curve $p = f(v)$:

Under standard conditions (perpendicular illumination on the photovoltaic cell surface E=1000 W/m², temperature T=25°C), the curve of electrical power output versus terminal voltage is shown in Figure (20) below



Fig(I.23): Power-Voltage Characteristics

Each point on the P-f(U) curve represents a certain power value, while point M corresponds to the maximum power that the cell can deliver. It is preferable for the cell to operate around point M

***Key features*:**

-Each point on P-V curve represents possible operating power

-Point M indicates maximum power output (P_{max})

-Optimal operation occurs near point M

I.14. The Photovoltaic System :

Photovoltaic energy is a renewable energy source derived from the sun. It directly utilizes solar radiation to convert light into electric current through the photovoltaic effect (Fig. I.24). Electricity is generated from daylight.

The conversion of light into electricity is achieved using photovoltaic modules, which consist of multiple interconnected solar cells. The electricity produced is in the form of direct current (DC).

To integrate it into the mains power supply or to operate devices that use alternating current (AC), the DC must be converted into AC using a DC/AC converter, also known as an inverter. This is particularly relevant for photovoltaic installations connected to a building's electrical system or the distribution grid, which currently account for nearly 90% of the global market.

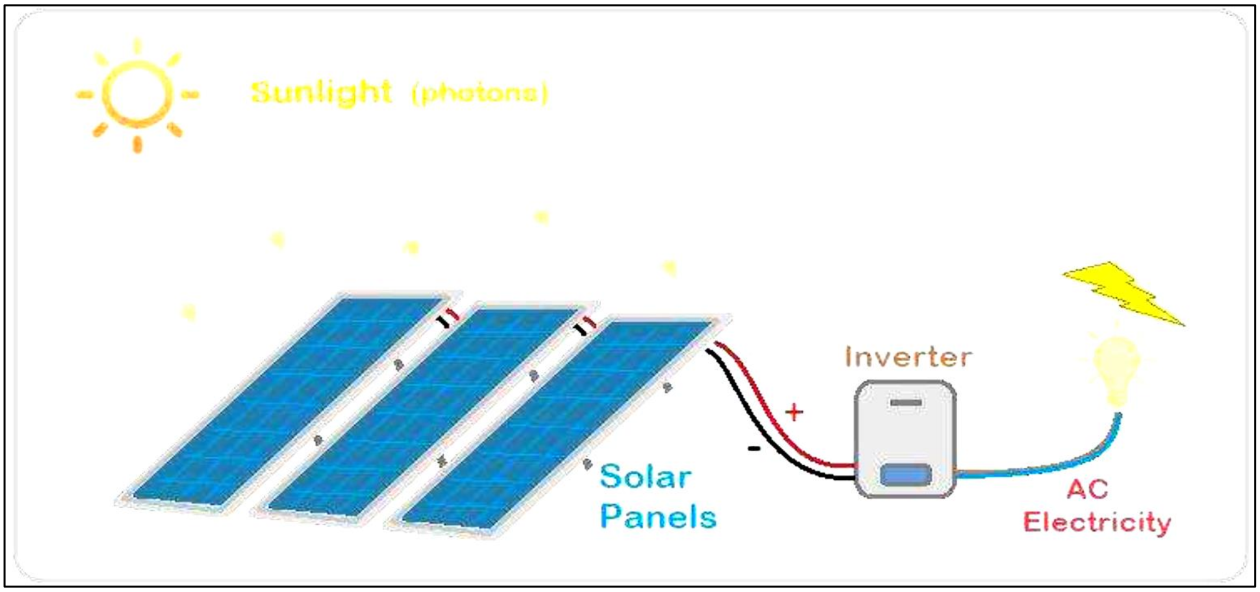
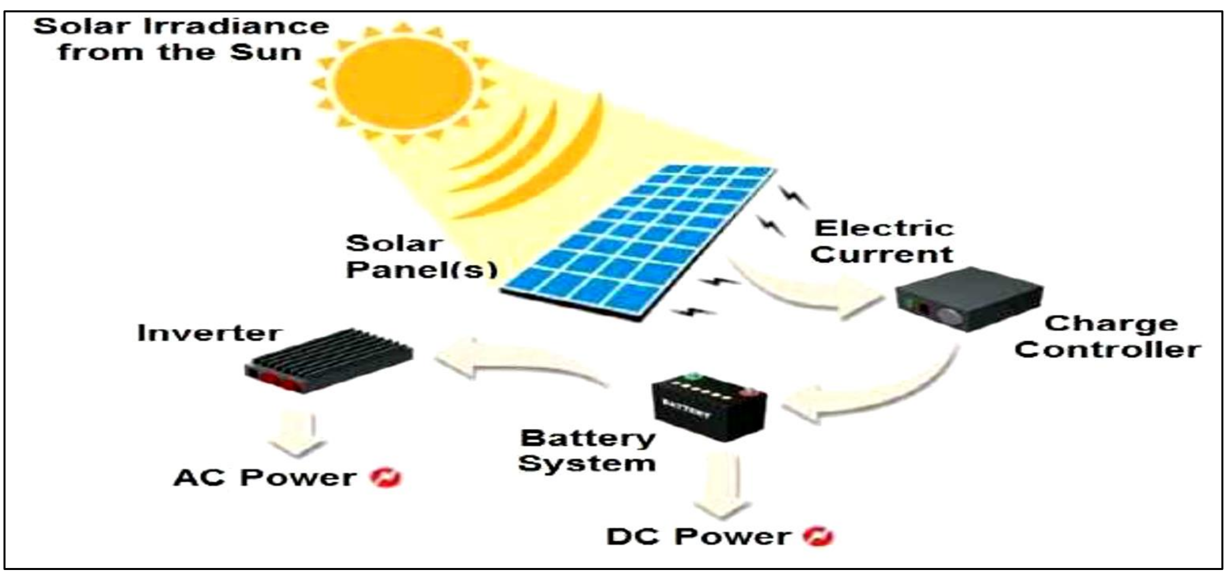


Fig (I.24) PV System

Photovoltaic modules must be combined with additional components to ensure a stable and reliable power supply. The complete setup forms a photovoltaic system (Figure I.25).



Fig(I.25) Components of a Photovoltaic System.

The environmental impact of this technology is minimal. It does not produce any significant nuisances, such as greenhouse gas emissions or waste. Most of its environmental footprint arises from energy consumption and the use of hazardous chemicals, like cadmium, during the manufacturing phase of the panels [1].

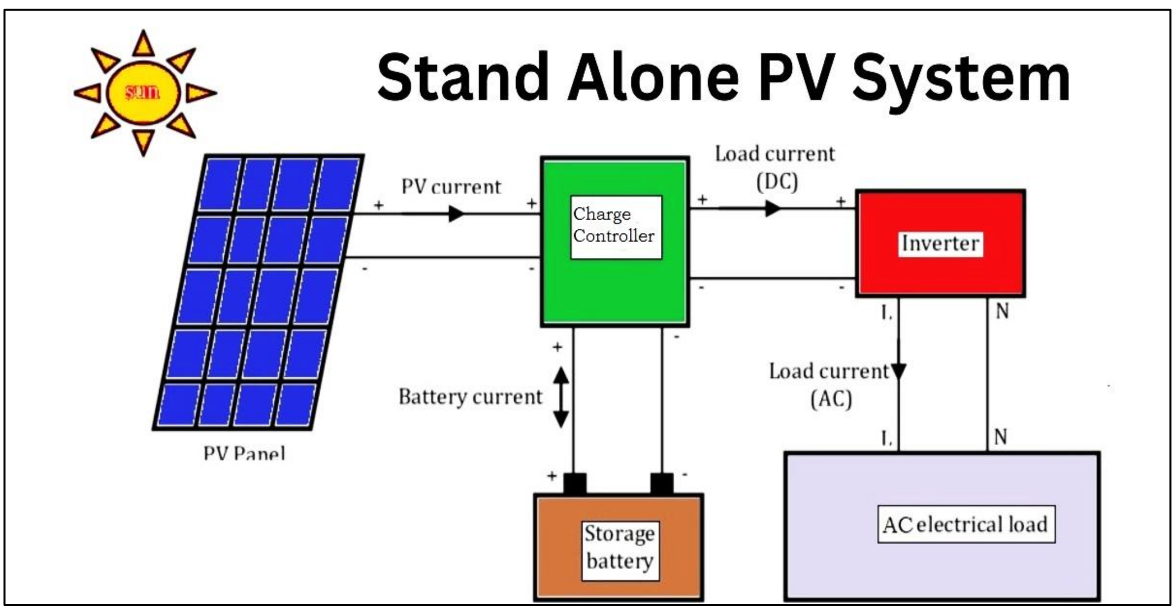
I.14.1. Types of Solar Photovoltaic Systems:

Based on the method of utilization, photovoltaic systems can be categorized into two configurations: - Stand-alone system - Grid-connected system

I.14.1.1. Stand-alone System:

In this system, power is supplied directly to a load without connection to a central grid or any other external power source, operating autonomously and independently. It is commonly used for backup power in areas where grid connection is impractical or too expensive. Stand-alone systems can power both DC loads and, when equipped with an inverter, AC loads.

Among the different types of stand-alone systems, the hybrid stand-alone system is the most widely used.



Fig(I.26) Hybrid Stand-alone System.

A hybrid stand-alone system integrates one or more additional power sources alongside photovoltaic (PV) panels. These supplementary sources may include generators, fuel cells, or AC mains. By combining multiple energy sources, reliance on a single power generation method is reduced. This approach also decreases the required battery storage capacity and the size of the PV array.

Stand-alone photovoltaic installations provide electricity for buildings or consumers not connected to the grid. The autonomous use of photovoltaic spans various fields, including:

- Space applications (space stations, satellites, etc.)

- Professional applications (communications, transportation, street lighting, etc.)

- Domestic and agricultural applications (rural homes, farming operations, health centers, remote islands, etc.)

- Electronics (watches, electronic labels, calculators, etc.)

I.14.1.2. Grid-connected System:

In this system, the electricity generated by the PV array is fed directly into the grid or used to power AC loads. When the power production exceeds the local demand, the surplus energy is supplied to the commercial grid, integrating the system into a larger power network. An energy meter tracks the amount of electricity delivered to the grid.

This setup ensures efficient energy utilization, allowing excess power to be distributed rather than wasted, making grid-connected systems a key component of modern renewable energy infrastructure.

I.15. Solar Energy Potential and Development Program in Algeria:

Algeria boasts one of the world's largest solar energy potentials, with over 2,000 annual sunshine hours (reaching 3,900 hours in desert regions). Average daily solar irradiation exceeds (5 kWh/m²), totaling 1,700 kWh/m²/year nationwide [18].

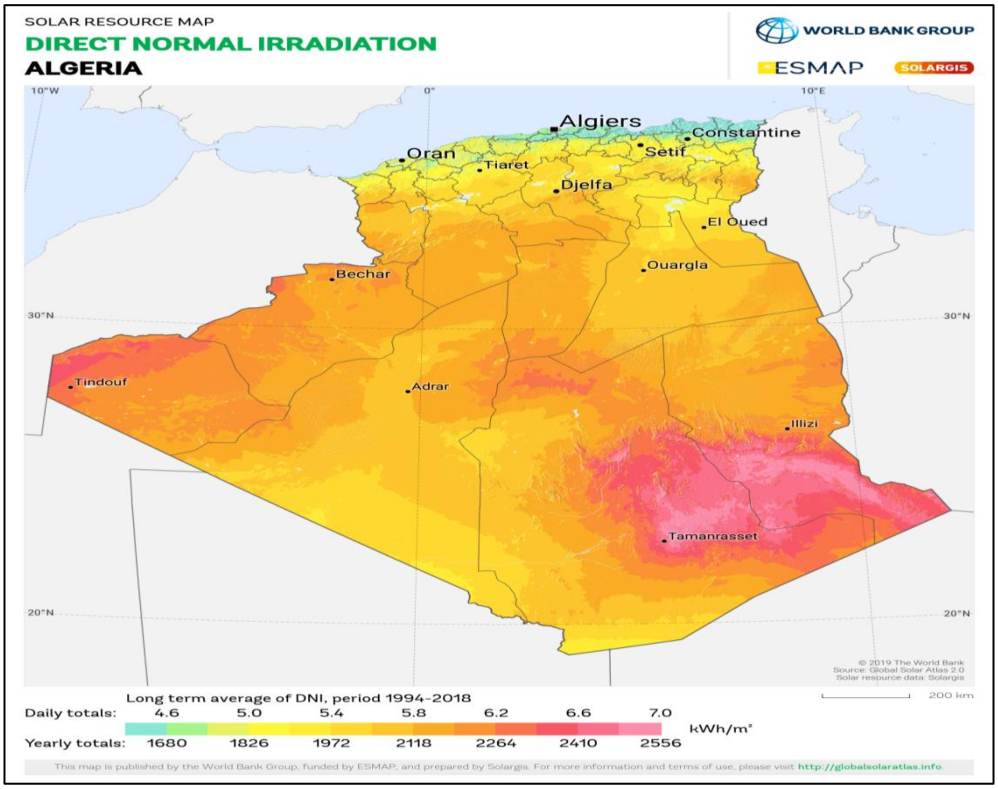


Fig.(I.27):maps Algeria's daily solar irradiation (Source: Solargis 2019).

The country plans to deploy 22,000 MW of renewable energy by 2035-2040, including a 4,050 MW photovoltaic mega-project divided into three 1,350 MW phases, coupled with local solar equipment manufacturing.

Algeria's installed PV capacity reached 74.1 MW by February 2016, with ongoing projects set to increase this figure [19].

I.16.Photovoltaic Energy Advantages and Disadvantages .

Table(I.2) Advantages and Disadvantages Photovoltaic Energy.

Advantages	Disadvantages
- Reliable & long-lasting with minimal maintenance - Vast potential (5% of deserts could power the world) . - Modular & scalable for flexible energy solutions . - Eco-friendly (no pollution, noise, or ecosystem harm) . - Reduces fossil fuel/nuclear dependence, cutting emissions and waste	- High production costs due to advanced technology - Low efficiency (max ~28% for silicon cells) . - Requires inverters to convert DC to usable AC power . - Battery storage increases costs but maintains reliability . - Weather-dependent (lower output on cloudy days).

I.17.Conclusion:

In this chapter, we presented an overview of photovoltaic systems, including solar cells, photovoltaic modules, and solar panels.

We explained the operation of photovoltaic cells as well as their types. Then, we discussed the structure of photovoltaic panels along with the different types of photovoltaic systems for residential use .

In the next chapter, we will introduce static DC/DC converters, which are buck-boost converters, as well as MPPT control.

Chapter II:

Maximum power point tracker of PV system

II.1. Introduction :

To maximize the performance of solar panels and achieve peak efficiency, it is essential to optimize the design of every component within the PV system. Furthermore, the DC/DC converters acting as the interface between the PV array and the load must be fine-tuned to continuously extract the maximum available power. This ensures the PV system operates at its Maximum Power Point (MPP) without energy losses by utilizing an MPPT controller. As a result, the system can deliver optimal power output despite fluctuations in load and changing environmental conditions (such as sunlight intensity and temperature).

Since the 1970s, numerous MPPT control strategies have been developed, ranging from basic techniques like voltage and current feedback-based MPPT controllers to more sophisticated algorithms that dynamically track the PV system's MPP. One of the most widely adopted methods is the Incremental Conductance algorithm. [21]

II.2. DC/DC Converters :

II.2.1. Definition:

The chopper, or DC-DC converter, is an electronic device that provides a constant DC output voltage with high efficiency. These converters consist of capacitors, inductors, and switching elements - typically MOSFET transistors operating in cut-off and saturation modes.

The converter's switch is controlled by a PWM (Pulse Width Modulation) signal (called MLI in French), operating at a fixed switching frequency Fs with a variable duty cycle α.

These converters enable controlled energy transfer between a power source and a load, which may be either capacitive (voltage source) or inductive (current source) in nature.

In principle, the input voltage is "chopped" at a specific frequency by the transistor switching alternately between ON and OFF states. This produces a square-wave voltage that is then filtered to obtain a smooth DC output voltage. [22] [23]

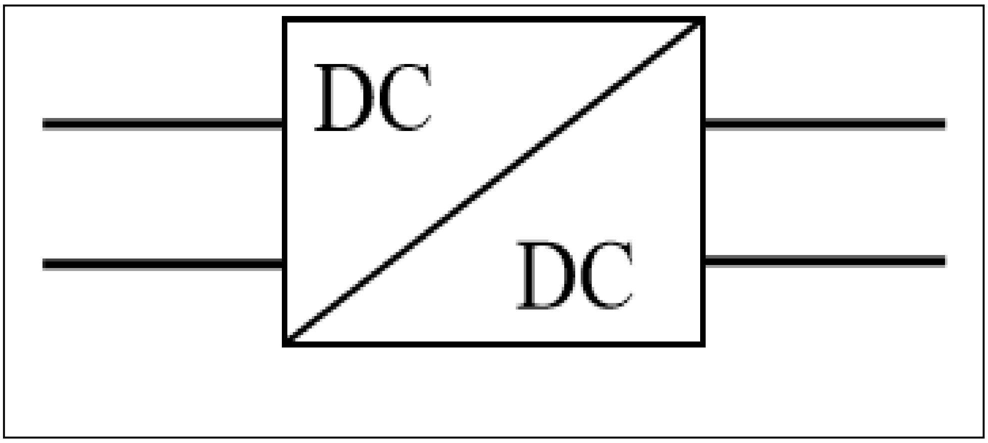


Fig (II.1): Symbol of a DC-DC Converter

When the transistor is switched on, the voltage across it remains low, minimizing power dissipation. Similarly, when the transistor is off, power loss is also low because the current flowing through it is negligible. The output average voltage is regulated by adjusting the pulse width, while the switching period *Ts* stays fixed. The duty cycle *d*(*t*), defined as the ratio of the pulse width to the switching period, determines this control and takes a real value between 0 and 1**[24].**

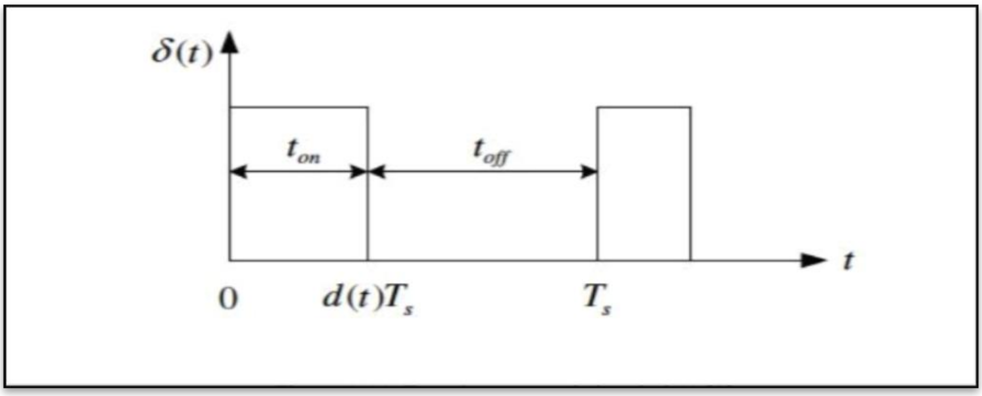


Fig (II.2): d (t), the transistor control signal [24].

II.2.2.Step-Up Converters (Boost Converters) :

The Boost converter, commonly known as a step-up converter, is designed to increase the input voltage to a higher level. As shown in the circuit diagram (Fig. II.3)**,** the converter operates in two key phases:

1. During the first phase (αT), the transistor (**S**) is closed (ON), causing the inductor current to rise gradually while storing energy in its magnetic field.
2. When the transistor (S) opens (OFF), the inductor (**L**) opposes the decrease in current (IL) and generates a voltage that adds to the source voltage. This combined voltage is then delivered to the load (R) through the diode (**D**). [25]

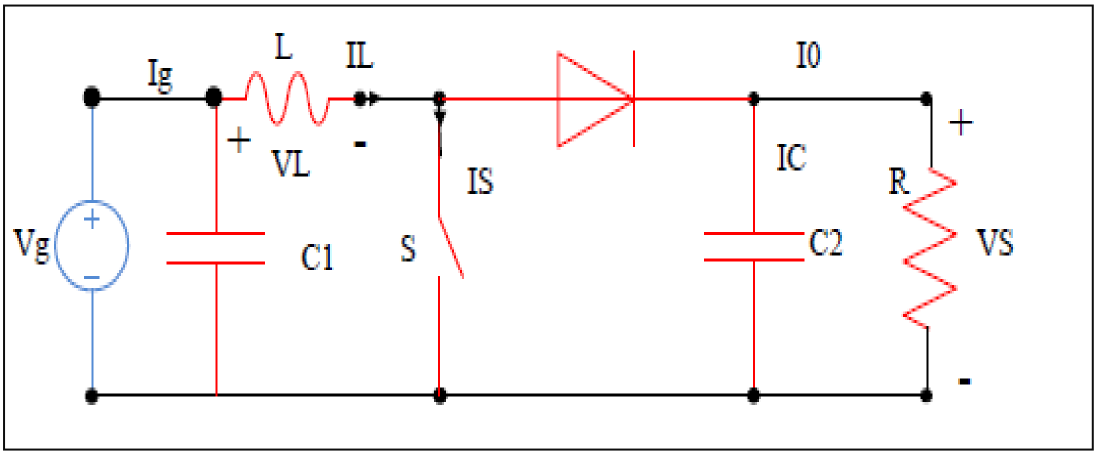


Fig (II.3): Basic electrical circuit of the boost converter

II.2.3. Equivalent Mathematical Model:

Applying Kirchhoff's laws to both equivalent circuits corresponding to the two operating phasesyields:

For the first interval (αTs):

$$\begin{cases} i_{C1}(t) = C_1 \frac{dv_g(t)}{dt} = i_1(t) - i_L(t) \\ i_{C2}(t) = C_2 \frac{dv_0(t)}{dt} = -i_0(t) \\ V_L(t) = L \frac{di_L(t)}{dt} = +V_g(t) \end{cases} \quad \textbf{(II. 1)}$$

For the second time period (1-α)Ts:

$$\begin{cases} i_{c1}(t) = C_1 \frac{dV_g(t)}{dt} = i_g(t) - i_L(t) \\ i_{C2}(t) = C_2 \frac{dv_0(t)}{dt} = i_L(t) - i_0(t) \\ V_L(t) = L \frac{di_L(t)}{dt} = V_g(t) - V_0(t) \end{cases} \quad \textbf{(II. 2)}$$

II.2.4. Approximate Model of the Boost Converter:

The Boost converter alternates between two states described by (Equ.2.1) and (Equ.2.2) during αTs and (1-α)Ts, respectively. To derive a unified dynamic model, we assume small signal variations, allowing us to approximate exponential changes (e.g. $e\epsilon \approx 1+\epsilon$) as linear segments with constant derivatives.

Thus, the average derivative of a variable $x(t)$ (e.g., inductor current or capacitor voltage) over one switching period Ts is

$$\frac{\mathrm{dx}}{\mathrm{dy}}\mathrm{T_s} = \frac{\mathrm{dx}}{\mathrm{dy}(\alpha\mathrm{Ts})} = \mathrm{T_s} + \frac{\mathrm{dx}}{\mathrm{dy}(1-\alpha)\mathrm{Ts})}(1-\alpha)\mathrm{T_s} \qquad \textbf{(II.3)}$$

"where ⟨dx/dy⟩ is the average value of the derivative of x over a period Ts. This relationship holds valid if **:**

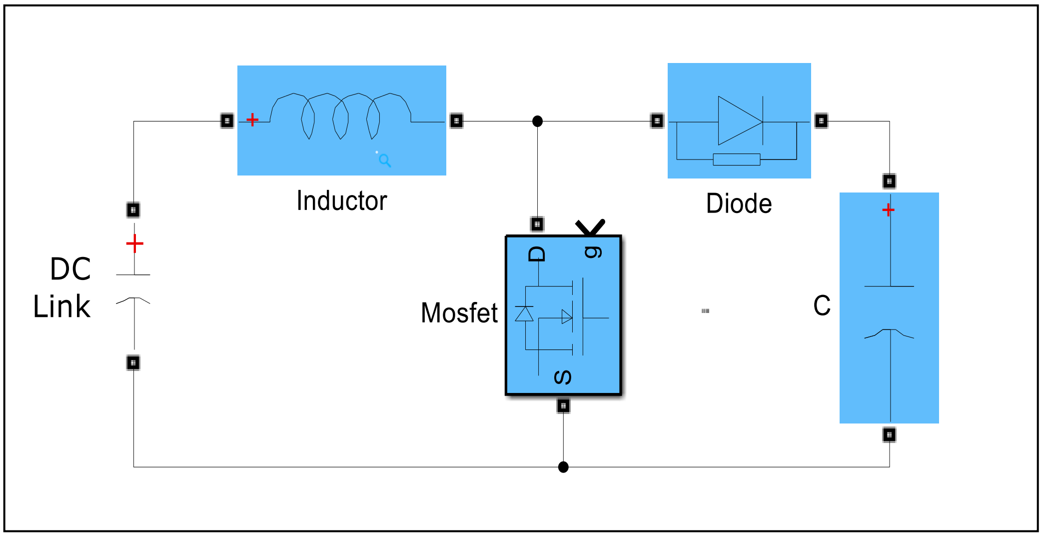
$$\frac{dx}{dy(\alpha Ts)}\, et\, \frac{dx}{dy(1-\alpha)Ts} \qquad \textbf{(II.4)}$$

remain constant during their respective intervals αTs and (1-α)Ts. This approximation remains valid when both switching intervals are significantly shorter than the dominant circuit time constants: the input time constant C_1Rg, the output time constant C_2Z, and the inductor time constant L/RL**.** [26]

We obtain the equations governing the system over a complete interval

$$\begin{cases} \mathrm{i_L} = i_g - \mathrm{C_1}\frac{\mathrm{dv_1(t)}}{\mathrm{dt}} \\ i_0 = (1-d)i_L - C_2\frac{dv_0(t)}{dt} \\ V_g = L\frac{di_L(t)}{dt} + (1-d)V_0 \end{cases} \qquad \textbf{(\textit{II}.5)}$$

II.2.5. Block diagram of a DC-DC converter:



Fig(II.4): Block diagram of a DC-DC converter

Table(II.1): Parameters the of DC-DC boost converter.

C1	C2	L
4700e-6	1200e-6	4e-4

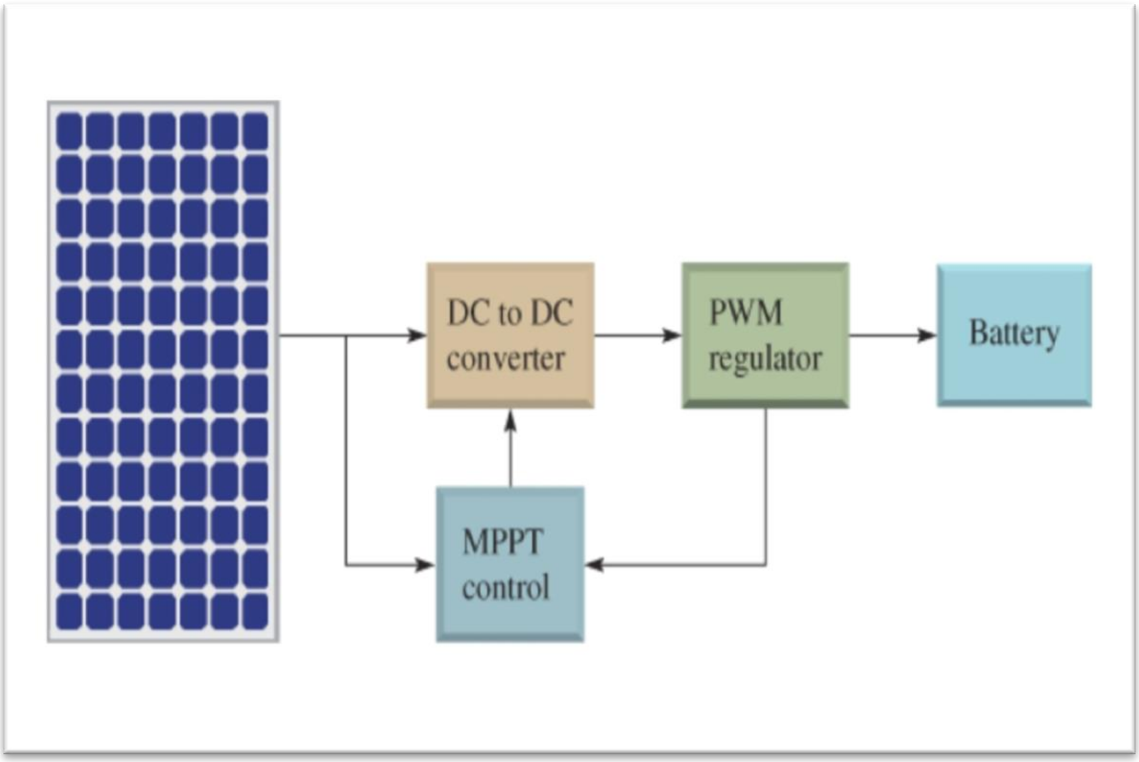
II.3. Advantages of the BOOST Converter :

A boost converter is employed to step up the voltage from a DC power source when higher output voltage is required. In battery-powered applications, series-connected cells are commonly used to achieve the necessary voltage level. However, physical space limitations often restrict the number of cells that can be implemented. By utilizing a boost converter, the system can effectively increase the battery voltage output, thereby reducing the required number of series-connected cells while maintaining the desired voltage level. This makes boost converters particularly valuable in photovoltaic systems and other space-constrained applications. [25]

II.4. MPPT Control:

As the name suggests, Maximum Power Point Tracking (MPPT) is a control technique designed to track the maximum power point of a photovoltaic system. It is typically integrated with an intermediate regulation stage that enables a photovoltaic generator to continuously deliver its maximum power by adjusting the duty cycle. The converter's control drives the system to operate at the maximum power point ($Vmpp$, **Impp**) under varying weather conditions (temperature and irradiance). Consequently, an MPPT controller regulates the static converter connecting the load to the photovoltaic module, ensuring the load receives maximum power at all times. [27]

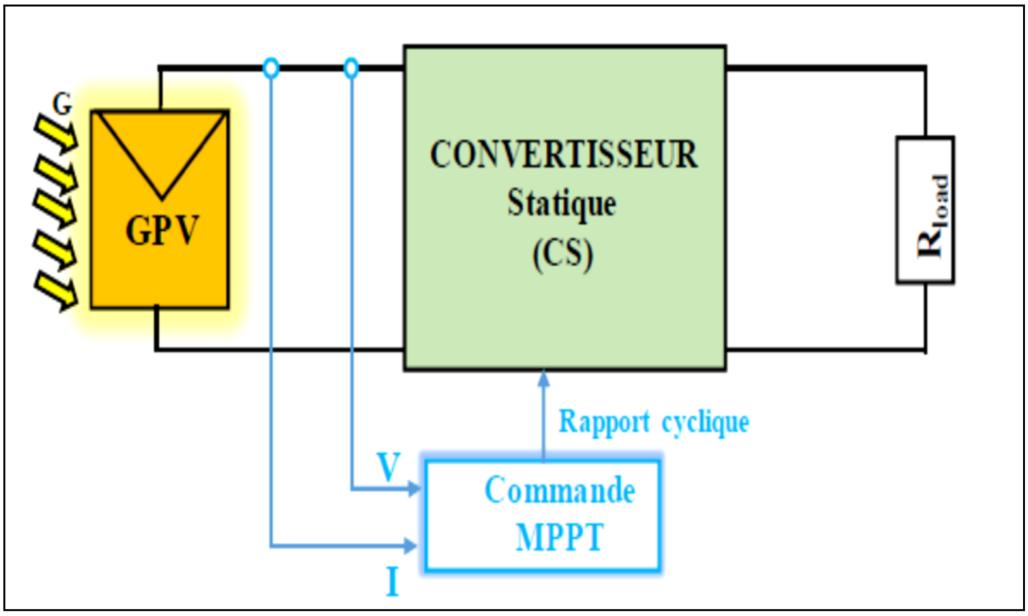
The studied system consists of the PV generator (GPV), a DC-DC converter, and a motor-pump group at the system output. The DC-DC converter is controlled by a Pulse Width Modulation (PWM) signal using an MPPT-based maximum power point tracking strategy.



Fig(II.5): Block diagram of a photovoltaic system with MPPT control. [28]

II.4.1. Principle of MPPT Control:

By definition, an MPPT control system, combined with an intermediate adaptation stage, ensures that a photovoltaic (PV) generator operates at its maximum power output at all times. Regardless of weather conditions (temperature and irradiance), the converter control adjusts the system to its maximum power point (MPP – *VPPM* and *IPPM*). The PV conversion chain is optimized using a static converter (SC) controlled by the MPPT algorithm [29]. This structure can be represented by the block diagram in Figure (II.6).



Fig(II. 6): Solar energy conversion chain consisting of a photovoltaic panel, a BOOST converter, an MPPT controller, and a load.

The MPPT control dynamically adjusts the static converter's duty cycle to maximize power extraction from the PV array. The algorithm's complexity depends on the MPP tracking method but generally relies on iteratively tuning the duty cycle in response to real-time current (I) and voltage (V) measurements—ensuring operation at the MPP (see Figure II.7)

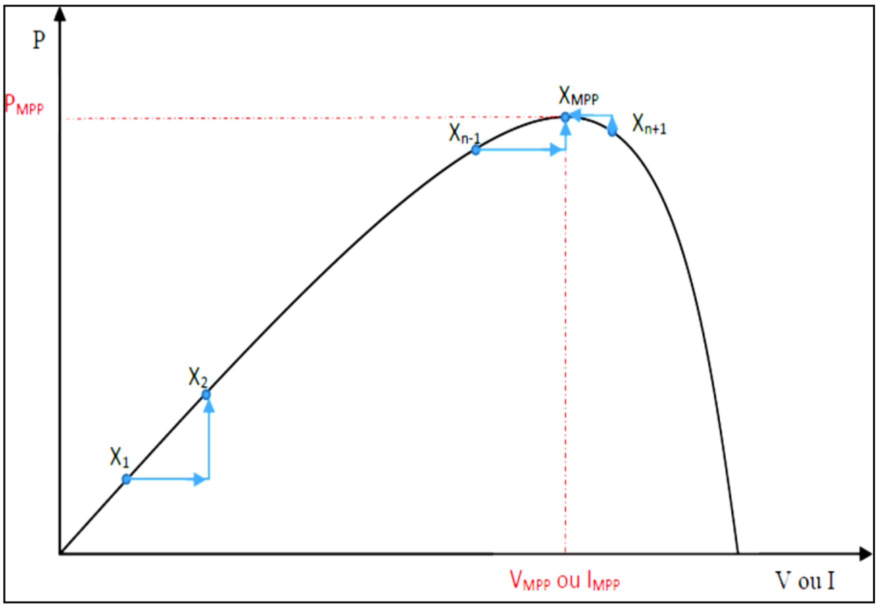


Fig (II.7): MPPT control principle.

II.4.2. MPPT Classification:

MPPT controllers can generally be classified by their electronic implementation (analog, digital, or mixed-signal), but a more technically relevant classification considers both their tracking algorithm methodology and the specific input parameters utilized by the control system. [30].

II.4.3 Classification of MPPT Controllers by Input Parameters:

A) MPPT Controllers Operating Based on Static Converter Input Parameters:

Several MPPT controllers perform MPP tracking by monitoring the power output variations from the PV generator, such as the Perturb & Observe method and Incremental Conductance algorithms, which use the PV system's power output to determine appropriate control actions for MPP tracking. Another category includes controllers based on proportional relationships between optimal parameters characterizing the maximum power point (Vopt and Iopt) and the PV module's characteristic parameters (voc and Icc), notably neural network-inspired MPPT approaches. These controllers either utilize extensive computer memory systems storing all possible cases or employ approximation techniques. All these methods offer the advantages of high precision and fast response times [30].

B) MPPT Controllers Operating Based on Converter Output Parameters:

In the literature, there also exist algorithms based on the output parameters of static converters (SCs). For example, MPPT controllers based on output current maximization are primarily used when the load is a battery.

In all systems using output parameters, an approximation of Pmax is made through the converter's efficiency. Essentially, the better the conversion stage performs, the more valid this approximation becomes. However, generally speaking, all single-sensor systems are inherently imprecise. Most of these systems were originally designed for space applications [30].

II.5. Classification of MPPT Controllers by Tracking Methodology:

II.5.1 Indirect MPPT:

This type of MPPT control utilizes the relationship between measurable variables (**Isc** or **Voc**), which can be easily determined, and the approximate position of the MPP. It also includes controls based on estimating the PV generator's operating point using a predefined parametric model. Additionally, some techniques track the optimal voltage by considering only temperature variations measured by a sensor.

These methods offer the advantage of simplicity in implementation. They are primarily designed for low-cost, low-precision systems operating in regions with minimal climatic variations. [31].

II.5.2 Direct MPPT:

This type of MPPT control determines the optimal operating point (MPP) by measuring the system's currents, voltages, or power levels. It can therefore respond to unpredictable changes in the PV generator's operation. Typically, these procedures are based on a search algorithm that continuously identifies the maximum point on the power curve without interrupting operation.

To achieve this, the operating voltage is incremented at regular intervals. If the output power increases, the search direction is maintained for the next step; otherwise, it is reversed. As a result, the operating point oscillates around the MPP. This basic principle can be enhanced in other algorithms to prevent misinterpretation errors, which may occur, for example, due to an incorrect search direction caused by a sudden power increase from rapid changes in irradiance.

Determining the PV generator's power value—essential for MPP tracking—requires measuring both voltage and current and computing their product. Other algorithms introduce small-signal sinusoidal variations to the converter's switching frequency, comparing the AC and DC components of the PV voltage to position the operating point as close as possible to the MPP. [31].

II.6. Maximum Power Point Tracking (MPPT) Search:

II.6.1. Initial MPPT Commands:

In January 1968, A.F. Boehringer published the first MPPT control law adapted to a photovoltaic-type renewable energy source. The control, based on an adaptive algorithm, ensures the system operates at its maximum power point. Using measurements of the photovoltaic panel's output current (Iph) and voltage (Vph), the method involves calculating the power at time ti and comparing it to the stored value at time ti-1. Subsequently, a new ratio [32].

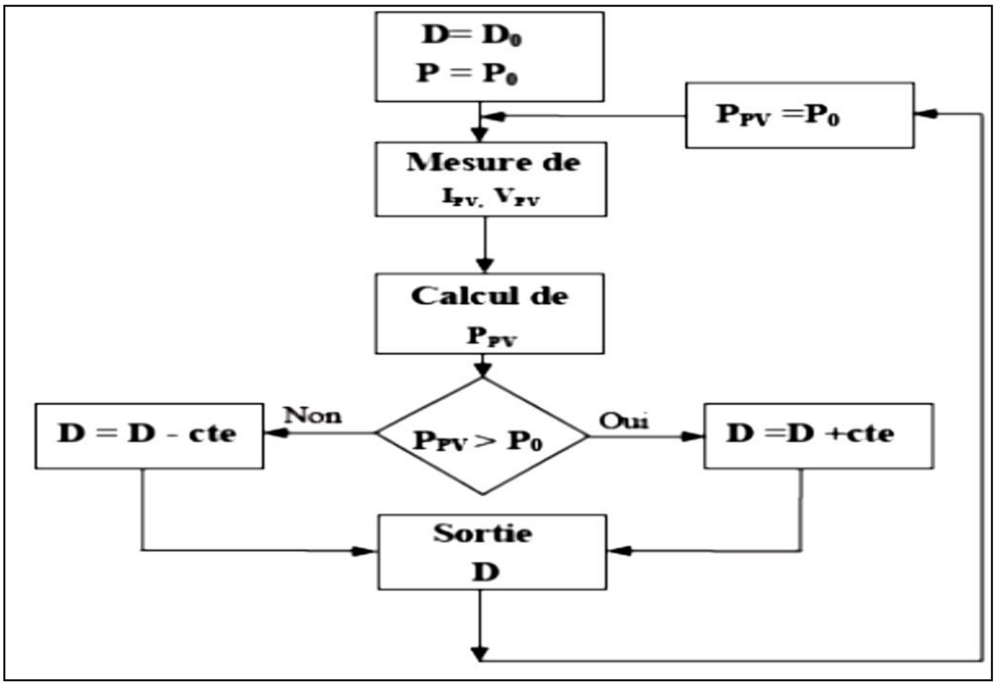


Fig (II.8): Principle of the first digital MPPT control.

II.6.2. Principle:

For a photovoltaic (PV) system to operate at the maximum power points of its current-voltage (I-V) curve, specific control laws must be implemented. This control mechanism is known in the literature as Maximum Power Point Tracking (MPPT).

The core principle of MPPT techniques is to continuously track the Maximum Power Point (MPP) while ensuring optimal impedance matching between the PV generator and the load, thereby maximizing power transfer efficiency.

As illustrated in **Figure (II.9)**, a basic PV conversion system incorporates an MPPT controller along with a static power converter. The MPPT algorithm dynamically adjusts the operating point of the PV array, forcing it to deliver its maximum available power to the load under varying environmental conditions.

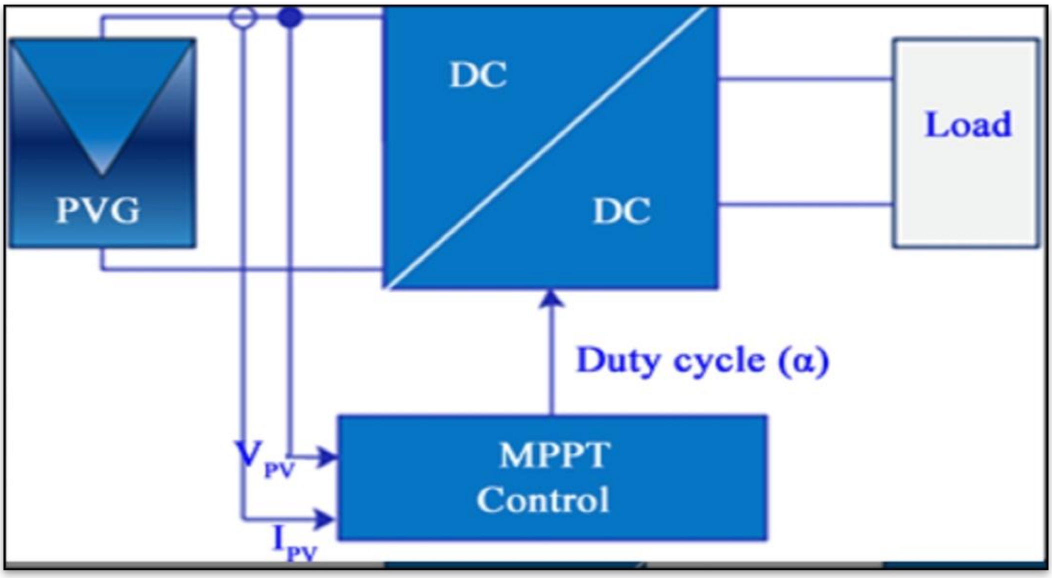


Fig (II.9): Photovoltaic conversion system with a static converter controlled by an MPPT algorithm. **[33]**

II.6.3. MPPT Control Methods:

The literature features numerous maximum power point tracking (MPPT) methods, among which the three most widely used techniques will be presented in the following discussion.

II.6.3. 1. Hill Climbing Method Principle:

The Hill Climbing control technique operates by perturbing the duty cycle while simultaneously adjusting the voltage. This perturbation causes the operating point to shift along the photovoltaic generator's power-duty cycle characteristic curve [34], as

illustrated in Figure (II.10).

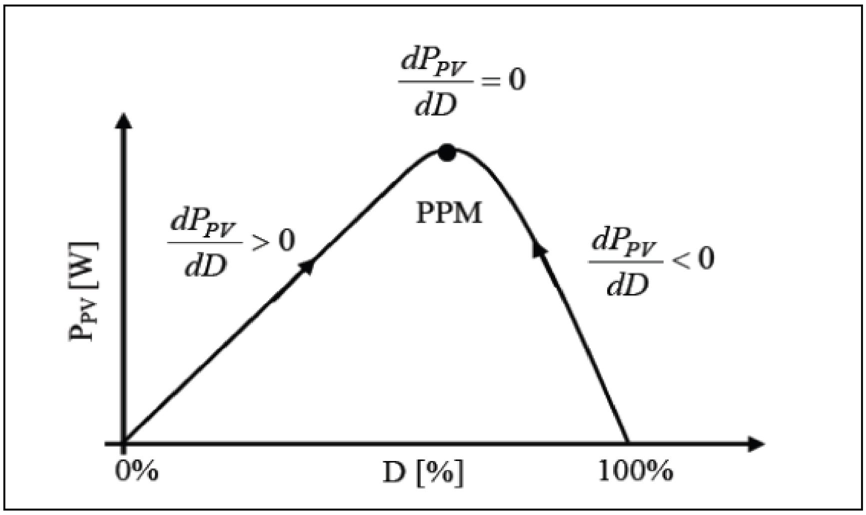


Fig (II.10): Relationship between power and duty cycle [34].

If a positive duty cycle increment increases power output, the operating point lies left of the MPP on the P-V curve, indicating the perturbation direction should be maintained [29]. Conversely, if power decreases, the operating point is right of the MPP and the perturbation direction must be reversed [34].

The algorithm uses:

- 'Sloop' variable: Takes values (1) or (-1) to determine the search direction for power maximization
- 'a' parameter: The duty cycle increment step size [34]

II.6.3.2 .The principle of the "Perturb and Observe" (P&O) method is:

The Perturb and Observe (P&O) technique is one of the most common Maximum Power Point Tracking (MPPT) methods because of its straightforward implementation [32]. The principle behind P&O is based on applying small perturbations (variations) to the solar panel's voltage and then evaluating how these adjustments affect the output power

to determine the optimal operating point [32].

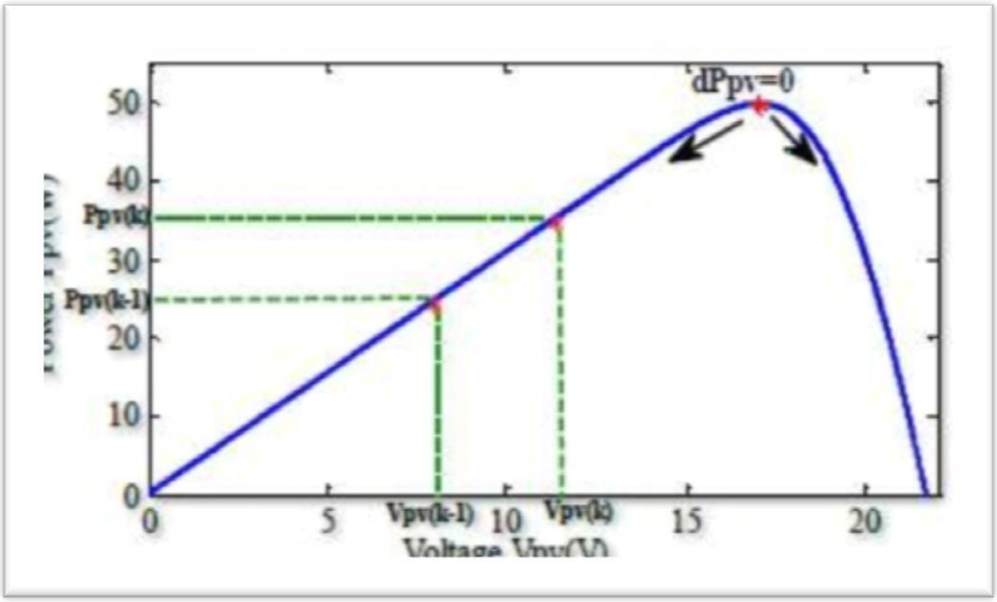
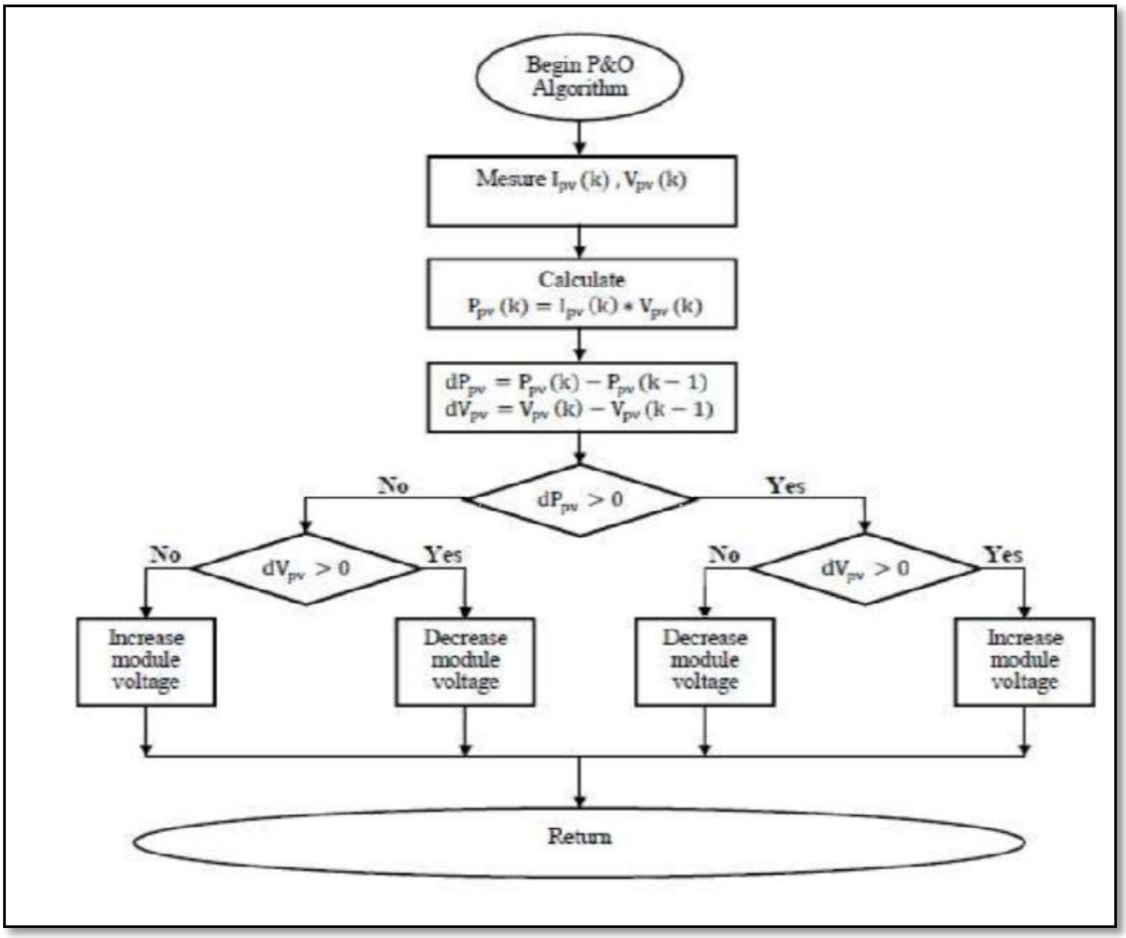


Fig II.11 characteristic for the P&O MPPT algorithm



FigII.12 MPPT algorithm disturb and observes (P&O)operating point.

II.6.3.2.1 Improvement of the disturbance and observation algorithm (P&O):

A key drawback of the perturb and observe (P&O) algorithm is its tendency to diverge under sudden changes in operating conditions. To address this issue, an enhanced version of the algorithm has been proposed. The improvement involves modifying the flowchart structure of the conventional P&O method by introducing an additional condition on the "yes" branch of the $\Delta Ppv(k) > 0$ decision step. Specifically, if the perturbation direction remains the same for two consecutive cycles, the next perturbation direction is reversed, regardless of the power measurement. This adjustment helps mitigate divergence and improves tracking performance during rapid operational changes [35].

II.6.3.2.2 Advantages and disadvantages of P&O :

Advantages:

✓ Simple control structure **.**

✓ Fewer measured parameters .

Disadvantages:

✓ **Overshooting the MPP** – Under rapidly changing atmospheric conditions (e.g., irradiance/temperature shifts), the system may deviate from the optimal maximum power point (MPP), leading to efficiency losses. **[35].**

II.6.3.3 Principle of the "Incremental Conductance" Method:

This method relies on analyzing the conductance variation of the PV system and its impact on the operating point. The instantaneous conductance and incremental conductance of the solar module are given by the following expressions

$$\mathbf{G} = \frac{\mathbf{I}\mathrm{pv}}{\mathbf{V}\mathrm{pv}} \qquad (\mathbf{II.6})$$

$$\mathbf{dG} = \frac{\mathbf{dI}\mathrm{pv}}{\mathbf{dV}\mathrm{pv}} \qquad (\mathbf{II.7})$$

(power-voltage) curve of the solar panel leads to the following operating conditions:

- $\frac{dPpv}{dVpv} > 0$, The operating point is to the left of the MPP (Maximum Power Point)
- $\frac{dPpv}{dVpv} = 0$, The operating point is at the Maximum Power Point (MPP).
- $\frac{dPpv}{dVpv} < 0$, The operating point is to the right of the MPP (Maximum Power Point).

Using relation (II.8), the derivative of power can be expressed in the form:

$$\frac{dPpv}{dVpv} = \frac{d(Vpv \cdot Ipv)}{dVpv} = Ipv.\frac{dVpv}{dVpv} + Vpv \cdot \frac{dIpv}{dVpv} = Ipv + Vpv \cdot \frac{dIpv}{dVpv} \quad (II.8)$$

Practically, like the P&O method, this technique exhibits oscillations around the MPP because it is difficult to perfectly satisfy the condition $\frac{dPpv}{dVpv} = 0$, which means the system continuously keeps searching for it.

The IncCond algorithm is more complex than P&O, resulting in a longer execution time [34].

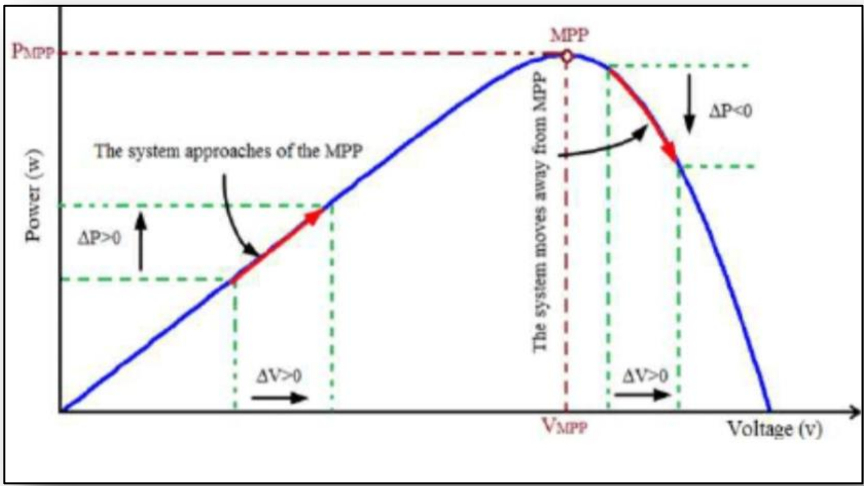


Fig (II.13): Illustration of the IC (Incremental Conductance) Method.

The voltage perturbation shifts the operating point closer to the MPP, and the voltage continues to be perturbed in the same direction. This progressively moves the operating point until the MPP is reached.

Conversely, if the power decreases (ΔP < 0), the operating point moves away from the MPP. In this case, the voltage must be perturbed with the opposite algebraic sign to redirect the operating point toward the MPP.

From these analyses of the effects of voltage variations on the (P-V) characteristic, it becomes straightforward to determine the operating point's position relative to the MPP and drive it toward maximum power through an appropriate control command. In summary, if a voltage perturbation leads to an increase in PV power, the perturbation direction is maintained. Otherwise, it is reversed to restore convergence toward the new MPP [34][36]

Figure (II.14) illustrates the conventional algorithm used in a P&O-based MPPT control, where the power variation is analyzed after each voltage perturbation.

According to this algorithm, two sensors (measuring the PV array's current and voltage) are required to determine the PV power at successive sampling instants and compute the voltage and power errors:

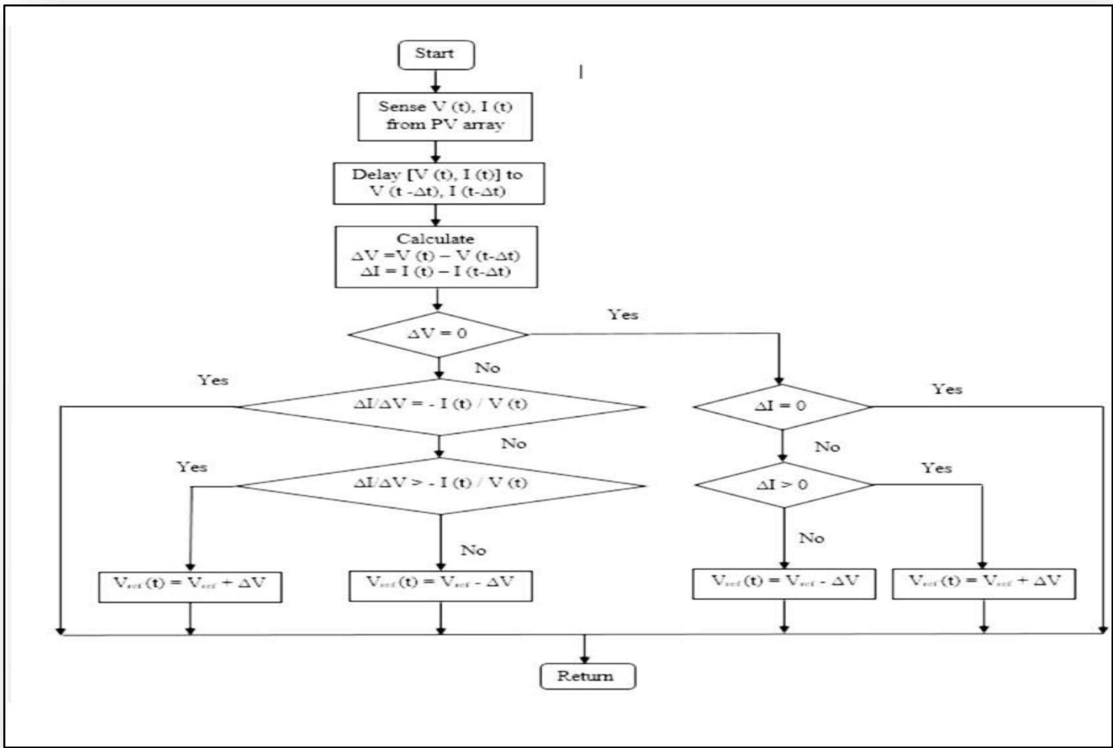


Fig (II.14): MPPT Technique Based on the IC (Incremental Conductance) Method.

The IC method is now widely used due to its simplicity. However, it suffers from certain issues related to steady-state oscillations around the MPP. This MPP tracking process must be repeated periodically, forcing the system to continuously oscillate around the MPP once it is reached. These oscillations can be minimized by reducing the perturbation step size. It should be noted that if the increment value is too small, the MPP search speed slows down significantly. In other words, a trade-off must be found between accuracy and response speed, making this control method challenging to optimize [36].

II.6.3.3.1Improved conductance increment method:

The conductance increment method can be enhanced using a two-stage approach: first, bringing the operating point near the maximum power point (MPP), and then applying the conductance increment algorithm for precise MPP tracking. Alternatively, integrating a PI (proportional-integral) corrector can further improve tracking accuracy and system response.

II.6.3.3.2 Advantages and Disadvantages of IC :

Advantage:

✓Simple control structure.

✓ Reduced number of measured parameters.

Disadvantages:

✓ Exceeding the optimal maximum point during rapid atmospheric changes [37].

II.7. SIMULINK Model of a Photovoltaic Panel Controlled by an IC:

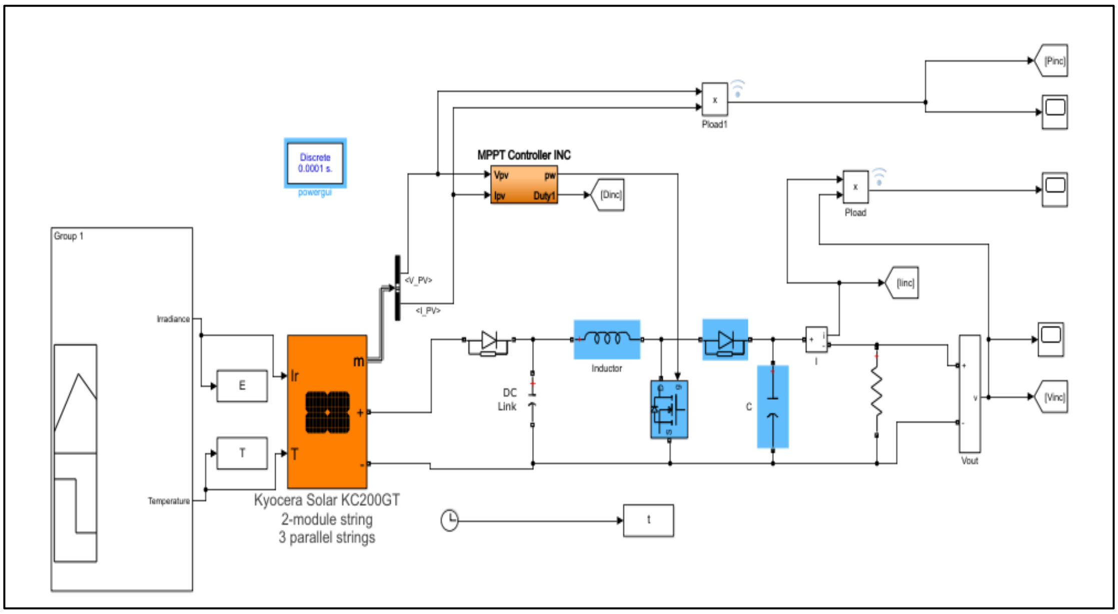


Fig (II.15): MATLAB SIMULINK Diagram of a Photovoltaic Panel Controlled by an IC.

Comment:

The figure below presents the power-voltage (P-V) curve of a 200W photovoltaic panel system controlled by an IC-based charge controller under variable temperature and solar irradiance conditions, demonstrating the system's performance across different operating environments.

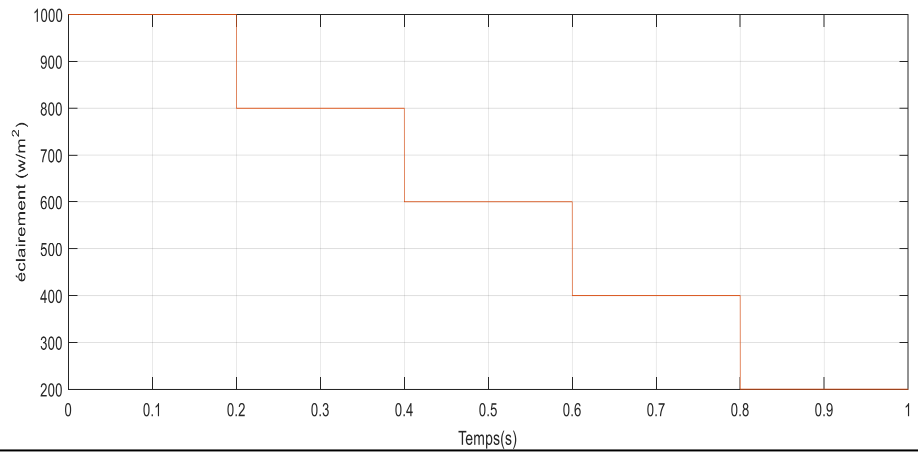


Fig (II.16): *Variation in illumination.*

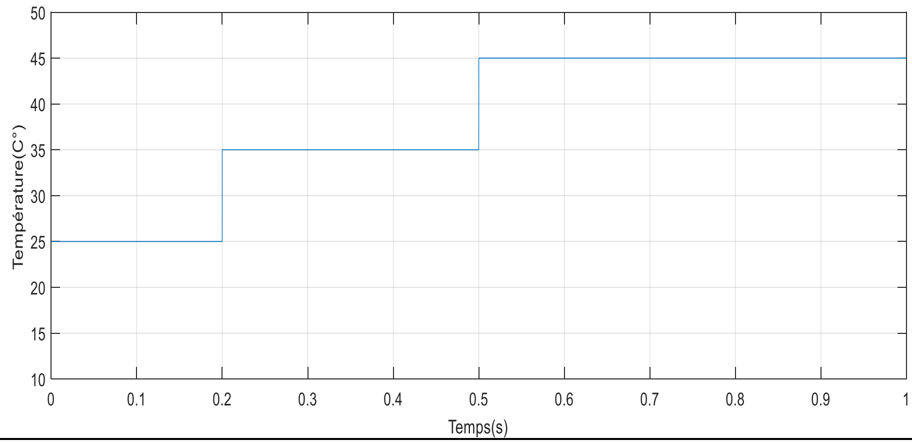


Fig (II.17): *Temperature variation.*

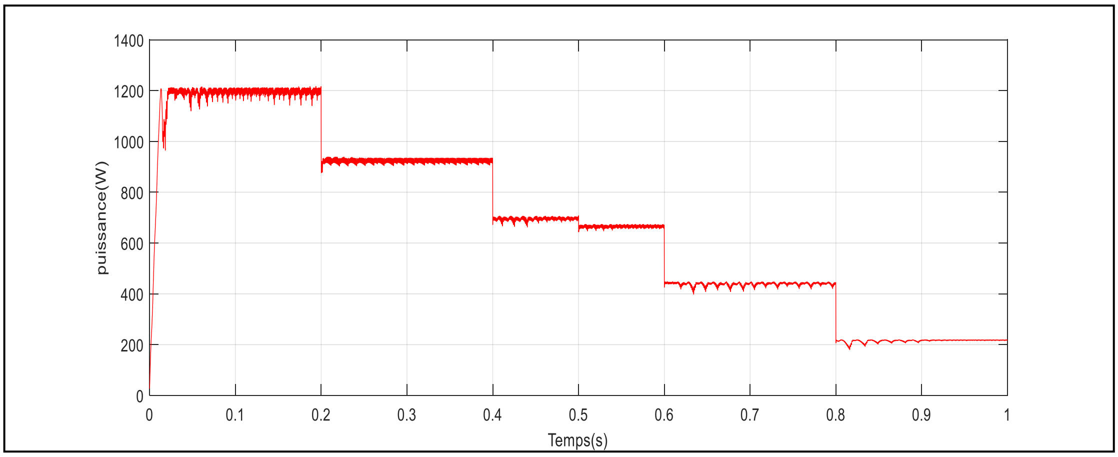


Fig (II.18): *P(t) Characteristics of a PV System.*

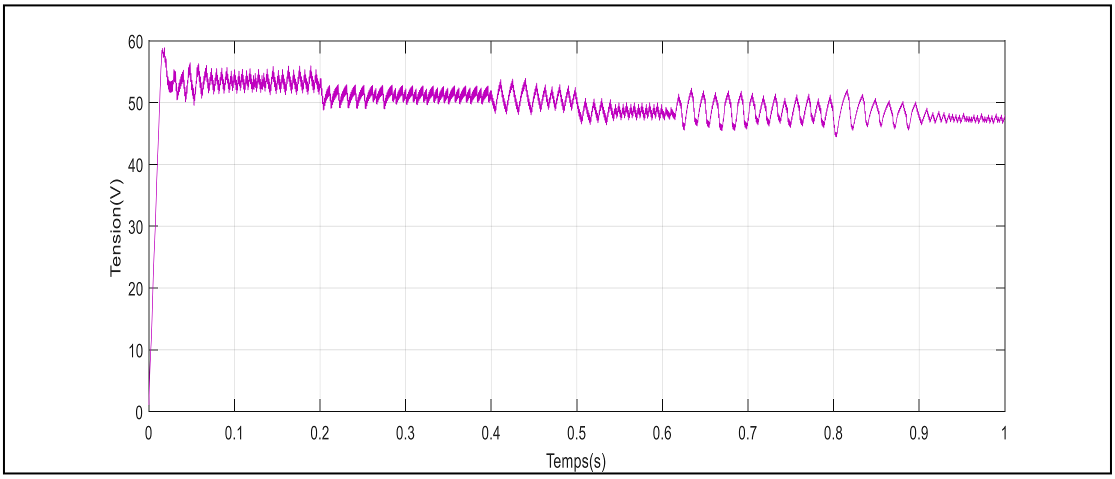


Fig (II.19): *v(t) Characteristics of a PV System.*

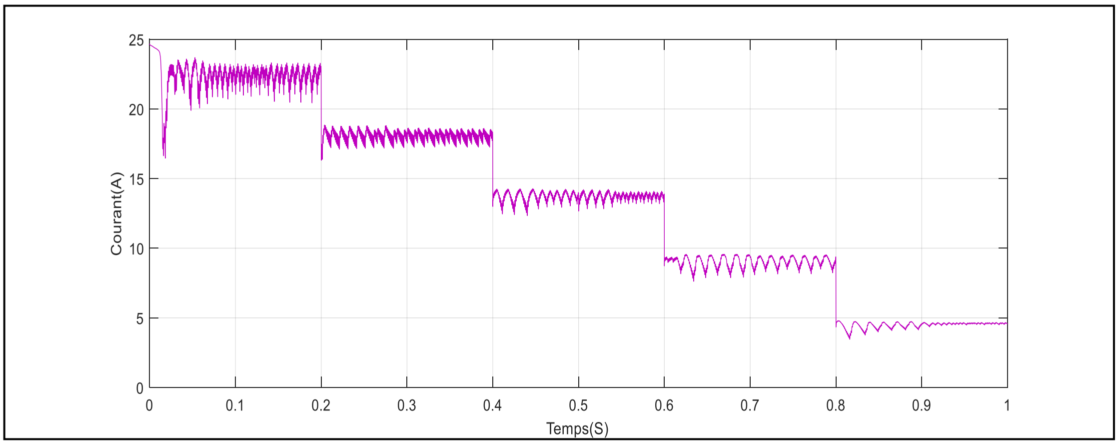


Fig (II.20): *i(t) Characteristics of a PV System.*

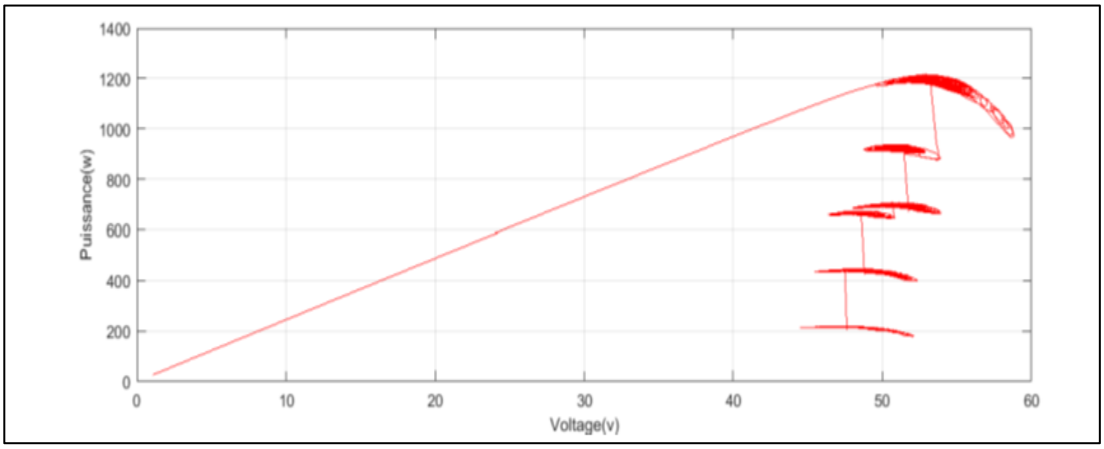


Fig (II.21): *P-V Characteristics of a PV System.*

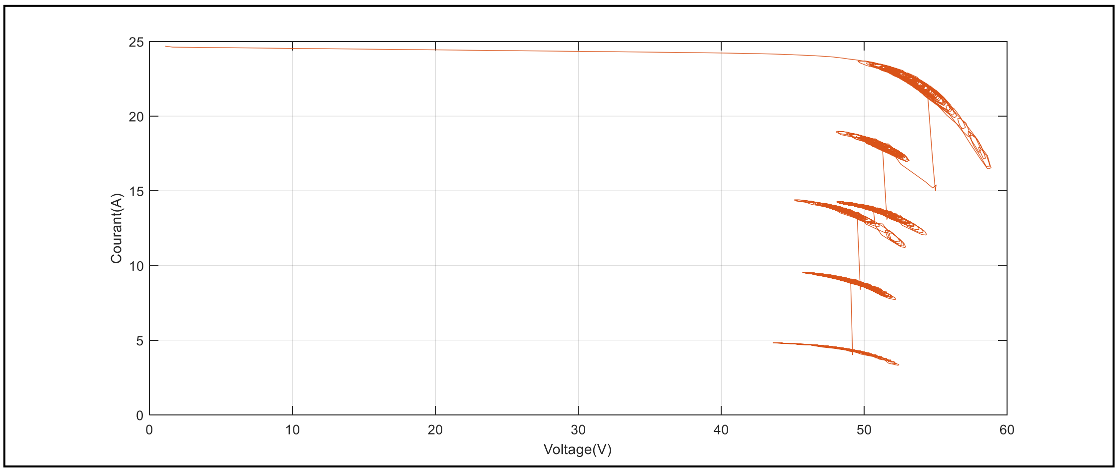


Fig (II.22): I-V Characteristics of a PV System.

Comments on figures:

Figure (II.18) shows the power-time characteristics of a photovoltaic system controlled by an IC regulator under varying temperature and irradiance conditions. The waveform exhibits a 0.01-second oscillation period before stabilizing at the maximum power output of 1200W, demonstrating the controller's dynamic response to environmental fluctuations. This transient behavior highlights the system's rapid convergence to optimal operating conditions despite variable inputs.

Figures (II.18), (II.19), and (II.20) present the power and voltage versus time characteristics of a photovoltaic system controlled by an IC-based MPPT controller under variable temperature and irradiance conditions. The system was subjected to irradiance steps (200, 400, 600, 800, and 1000 W/m²) at t=1s while operating at varying temperatures (25°C, 35°C, and 45°C). The results demonstrate that increasing voltage leads to decreasing power, causing the operating point to deviate from the MPP. The controller effectively restores operation near the MPP within 0.01 seconds, though with minor oscillations attributable to the control algorithm's dynamics [38]. These transient responses illustrate the system's ability to maintain MPP tracking despite rapid environmental changes.

II.8. Conclusion:

This chapter presented a simulation study of Maximum Power Point Tracking (MPPT) using the Incremental Conductance (IC) method. This power feedback-based control approach directly utilizes photovoltaic panel voltage and current measurements to dynamically track the operating point corresponding to maximum power output.

The following chapter will introduce an intelligent control approach (Fuzzy Logic-based MPPT) designed to enhance the performance of photovoltaic system control. This advanced method aims to improve tracking efficiency and system response under varying environmental conditions.

Chapter III:

Fuzzy logic MPPT controller

III.1. Introduction :

Fuzzy logic, introduced in 1965 by Lotfi Zadeh based on his mathematical theory of fuzzy sets, extends classical logic to model imperfect data. It mimics human reasoning flexibility and has recently been applied in maximum power point tracking (MPPT) systems.

In 1973, Zadeh introduced the concept of linguistic variables, where values are words rather than numbers. A year later, Mamdani developed an experimental fuzzy controller for a steam engine. By the 1980s, fuzzy logic saw widespread adoption, particularly in Japan, across various control and regulation applications.

This chapter explores fuzzy logic, its principles, components, and operation, as well as its application in photovoltaic MPPT control [39].

III.2. Fuzzy Logic Definition:

Fuzzy logic is an extension of Boolean logic that processes imprecise knowledge using linguistic terms. It translates human-like reasoning into automated control by introducing the concept of partial truth, allowing conditions to exist in states beyond just "true" or "false." This flexibility enables handling uncertainties and imprecisions, making it suitable for controlling complex systems with vague or incomplete information.

A key advantage of fuzzy logic is its ability to formalize human reasoning through rules expressed in natural language [40].

III.2. Fuzzy Logic Fundamentals :

Fuzzy logic extends traditional binary logic by introducing intermediate truth values between absolute true and false. This approach enables the processing of ambiguous or qualitative data through linguistic variables, mimicking human decision-making patterns. Its ability to handle imprecise information makes it particularly valuable for controlling complex, real-world systems where exact mathematical models may be unavailable.

The methodology's strength lies in its use of intuitive, language-based rules that closely resemble human thought processes [40].

III.3. Fuzzy Logic-Based Algorithms:

Fuzzy logic-based MPPT control techniques have recently been introduced, offering robust control without requiring exact mathematical system models. These methods improve performance (convergence speed, accuracy, ease of implementation, and low cost).

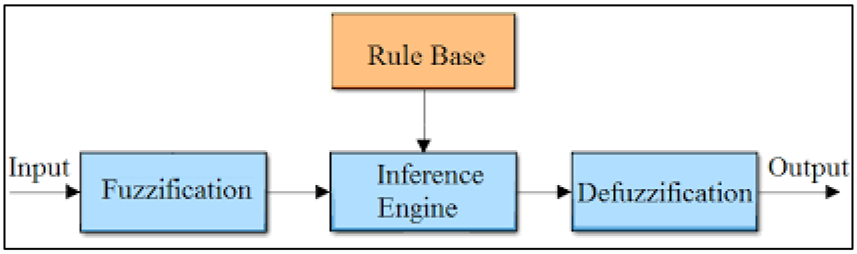


Fig.III.1: The fuzzy controller uses two input variables.

error (E) and error change (CE), with duty cycle variation (ΔD) as output to drive the power converter for MPP tracking [41] [42].

III.3.1. Fuzzification:

Fuzzification converts real variables to fuzzy variables. PV generator voltage (V) and current (I) are measured continuously to calculate power (P=V×I). The controller inputs are:

$$E(K) = P(K) - P(K-1) \qquad (III.1)$$

Inputs are scaled (E, CE) and converted to linguistic variables (n, z, p) using triangular membership functions

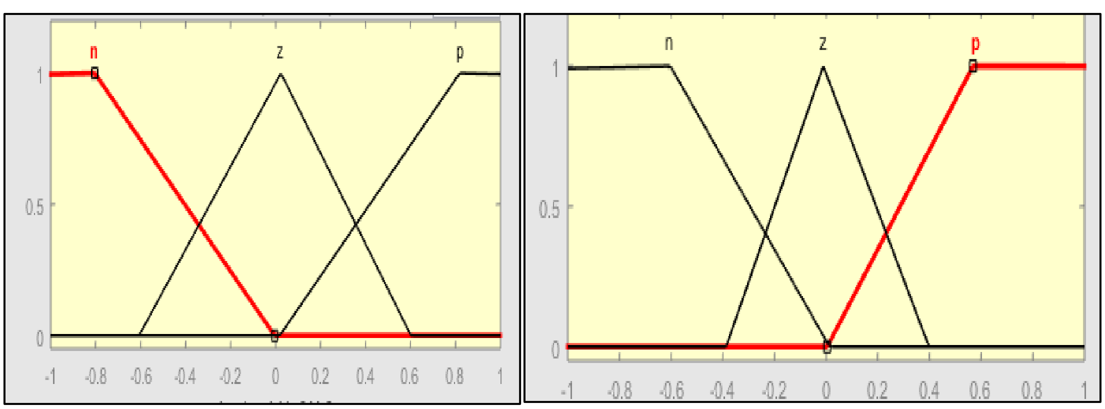


Fig (III.2)Input variable (E; CE)

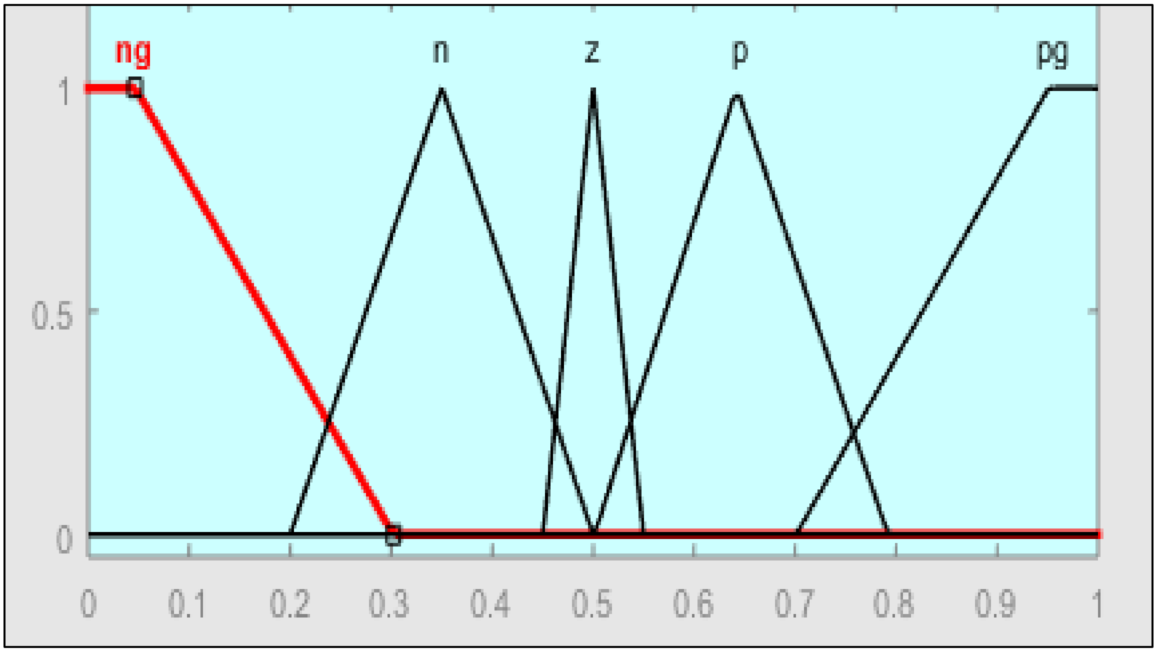


Fig (III.3). Output variable (ΔD)

III.3.2. Fuzzy Inference:

The inference stage establishes logical relationships between inputs/outputs using rule table

Table(III.1). Membership rules are applied to determine control actions.

CE \ E	N	Z	P
P	N	P	Ng
Z	N	Z	Pg
N	Ng	N	P

P: Positive . **N:** Negative . **Z :** Zero .

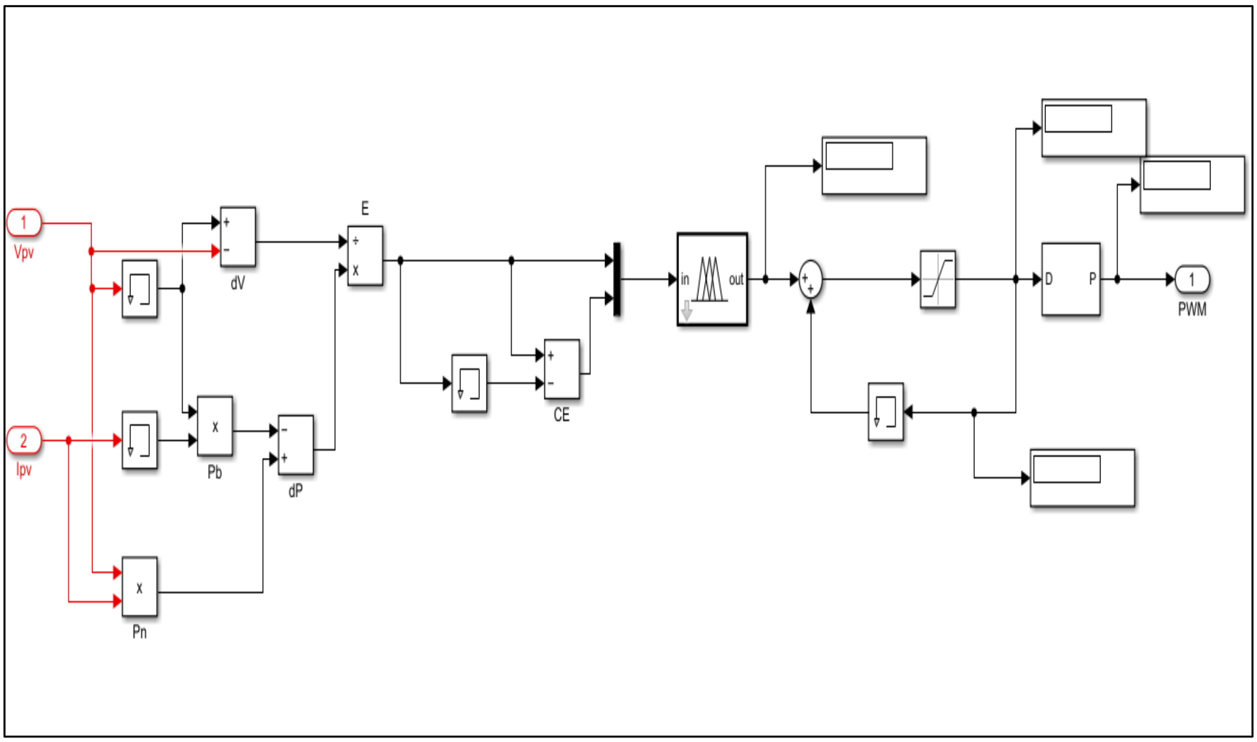
Ng: Negative large change in duty cycle. **Pg :** Positive change in duty cycle

III.3.3. Defuzzification:

The final step converts linguistic outputs to numerical values using the centroid method, calculating the center of gravity of the combined fuzzy set [43].

III.4. Fuzzy MPPT Simulation Results:

The fuzzy MPPT method intelligently controls PV system maximum power points. Using the same simulation model as INC MPPT with modified E/CE calculations and duty cycle adaptation,



Fig(III.4) fuzzy MPPT cntrol block diagram.

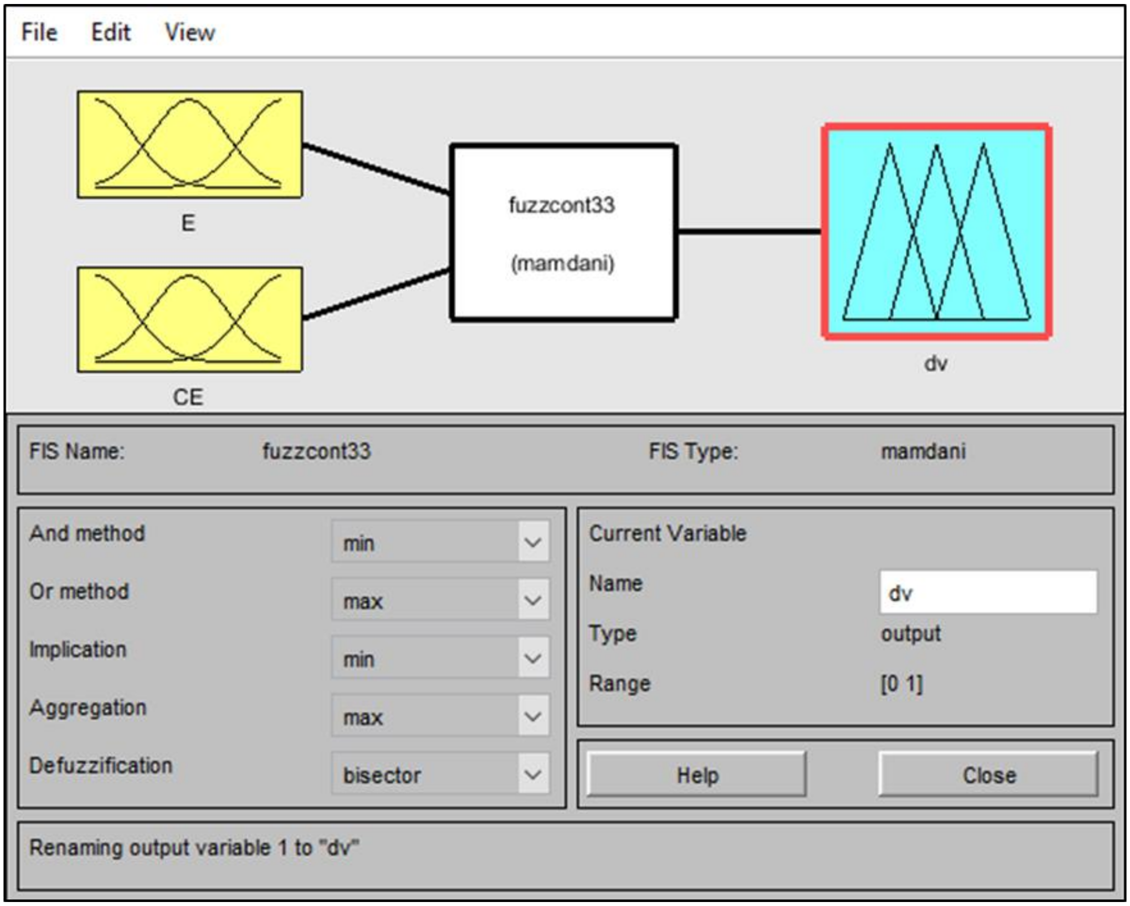
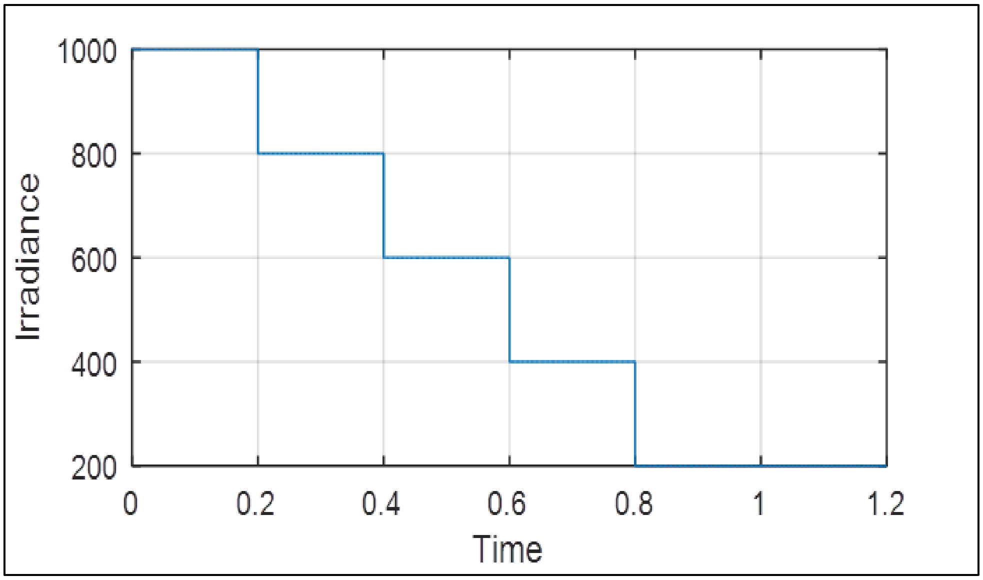


Fig (III.5) General Structure of Fuzzy MPPT Controller

To evaluate the robustness of the fuzzy MPPT controller under varying environmental conditions, we conducted the same tests used fo the INC method.

III.4.1 Operation under Variable Temperature and Irradiance:

Using the same temperature and irradiance profiles shown in Figures (III.6) and (III.7), we compared both techniques while maintaining different temperature and irradiance values.



Fig(III.6) : irradiance profile over time.

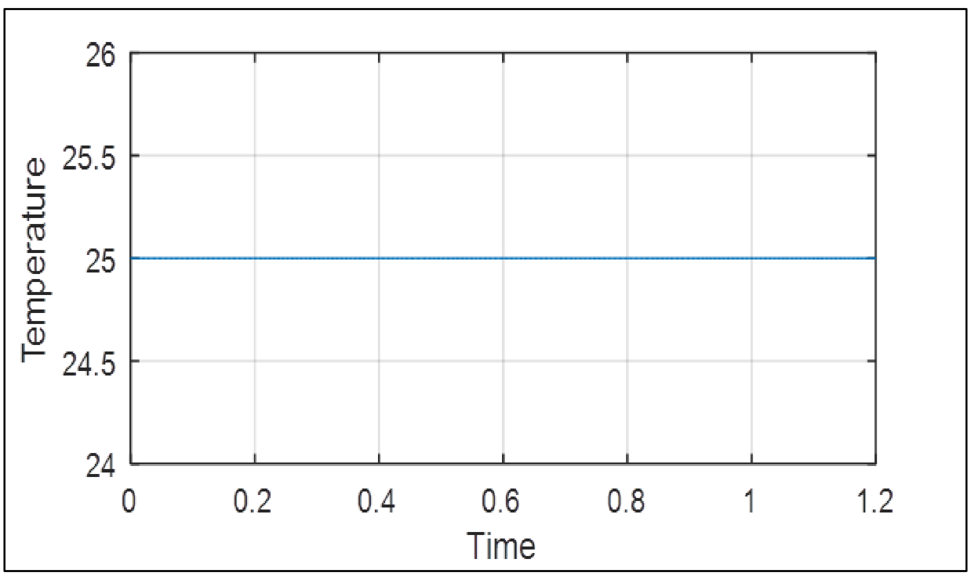


Fig (III.7): temperatures profile over time.

III.5 Comparison between INC and Fuzzy Logic MPPT Methods:

For irradiance decreasing from 1200W/m² to 200W/m², both INC and fuzzy MPPT methods produced the results shown in Figures (III.6), (III.7), and (III.8):

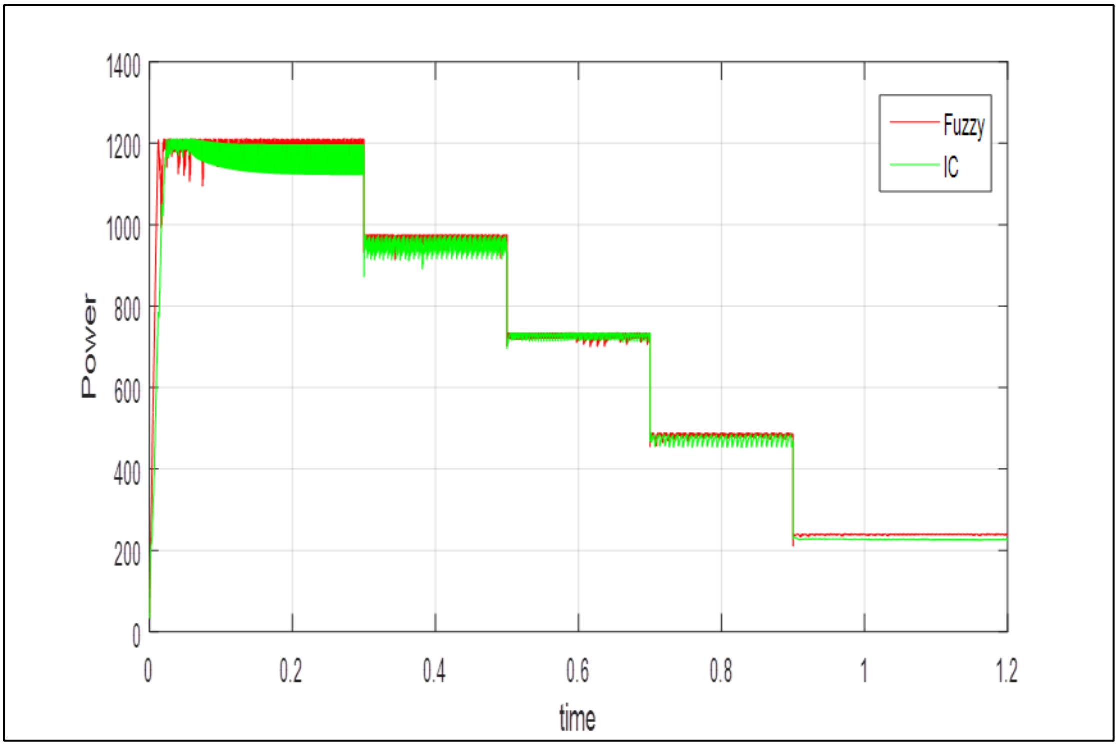
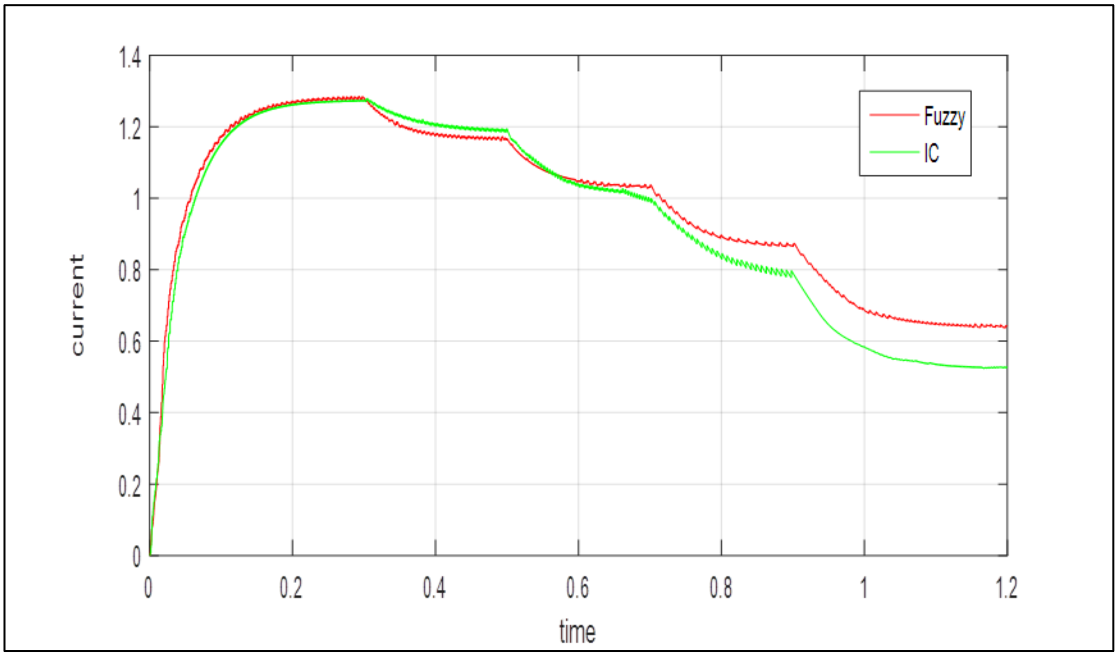
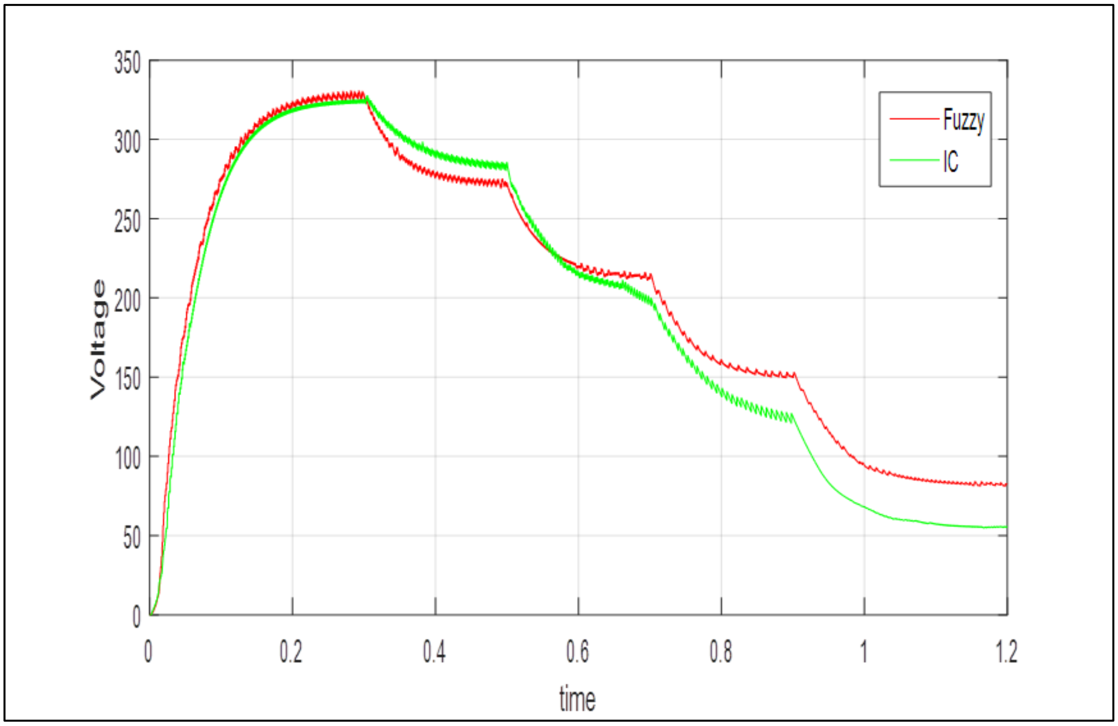


Fig (III.8): Power variation over time (Fuzzy vs INC)



Fig(III.9): Current variation over time (Fuzzy vs INC)



Fig(III.10): Voltage variation over time (Fuzzy vs INC)

✓ From the previous figure, the advantages of the fuzzy logic-based MPPT control are clearly observed. The fuzzy MPPT control (in blue) is robust and exhibits faster response times, higher accuracy, and a very small steady-state error compared to the IC-based MPPT control. To better visualize the difference between the two control methods, refer to figures (III.8), (III.9), and (III.10).

✓ The results obtained with the proposed fuzzy control technique are superior to those achieved with conventional IC-based control methods. Thus, fuzzy logic control can be seen as a step toward bridging the gap between precise mathematical control and human-like decision-making. Additionally, these results confirm the proper functioning of the IC controller but demonstrate better performance of the fuzzy control. This is further supported by the results obtained after combining the two methods, which proved to have even better performance—fast response time, very low steady-state error, and almost no overshoot.

✓ A comparative study of the two proposed control methods (classical and modern) showed that the fuzzy logic-based controller optimizes the system's operating power more effectively.

III.6. Conclusion:

In this chapter, we presented the two control methods for maximum power point tracking (MPPT): the classical IC method and the intelligent fuzzy logic-based MPPT control. We implemented the necessary simulation blocks using simulation software. Different results were obtained for varying solar irradiance and temperature levels for both the fuzzy MPPT control and the IC-based MPPT algorithm. These results confirm the proper functioning of the fuzzy control. Superior performance of than IC- MPPT . when the the simulation of the fuzzy MPPT control showed better performance, including faster response times, very low steady-state error, and robustness against variations in atmospheric conditions.

General conclusion :

Because of the industry's recent explosive growth and expansion, natural energy resources like uranium, gas, and oil are running low. The energy requirements of the world are likewise rapidly evolving. To address our energy needs, we are researching renewable energy sources. One of the renewable energy sources that can satisfy demand is photovoltaic solar energy, which is also clean, quiet, affordable, and widely accessible. This explains the significant global expansion in its use. First, we investigated photovoltaic energy from the sun. We discussed the components of the system. We then talked about ways to keep an eye on the maximum power point. To monitor the I-V and P -V characteristics at different temperatures and irradiances, we have developed MATLAB simulation algorithms. In the MATLAB simulator, we evaluated a solar system with a boost converter and MPPT controls using an IC first, followed by a fuzzy controller .

To better understand the difficulties of operating a solar system, we considered variations in temperature, illumination, and other meteorological factors. The findings are satisfactory, and the tracking time and peak power point completion accuracy for the various operating conditions are good. According to the comparison, the fuzzy logic performs better than IC.

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