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Dedication

To our beloved parents,
Your unwavering support, love, and prayers have been the foundation of our journey. We owe you everything, and this work is dedicated to you with deep gratitude.

To our families and friends,
Thank you for being our pillars of strength throughout this academic path. Your encouragement has meant the world to us.

We would like to express our heartfelt thanks to:

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For his sincere dedication, continuous support, and valuable guidance. His involvement and encouragement have been instrumental in the completion of this work.

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To everyone who inspired, supported, or stood by us—
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Abstract

The aim of improving the efficiency of photovoltaic systems is to maximize energy extraction from solar panels using Maximum Power Point Tracking (MPPT) algorithms. These include Perturb and Observe (P&O), which is simple but suffers from oscillations; Incremental Conductance (INC), which offers greater accuracy under dynamic conditions; and the Fuzzy Logic Controller (FLC), which relies on artificial intelligence and provides faster responses to changing environments. Combining these algorithms enhances overall system performance by integrating the simplicity of P&O, the accuracy of INC, and the speed of FLC, thereby increasing the system's efficiency under various environmental conditions.

Keywords: Photovoltaic systems, Maximum Power Point Tracking (MPPT), Incremental Conductance (INC), Fuzzy Logic Controller (FLC), Energy extraction, Efficiency improvement

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الملخص:

يهدف تحسين كفاءة الأنظمة الكهروضوئية إلى تعظيم استخلاص الطاقة من الألواح الشمسية باستخدام خوارزميات تتبع نقطة القدرة القصوى .(MPPT) وتشمل هذه الخوارزميات خوارزمية الاضطراب والمراقبة (P&O)، وهي خوارزمية بسيطة ولكنها تعاني من التذبذبات، وخوارزمية التوصيل التزايدي(INC)، التي توفر دقة أكبر في الظروف الديناميكية، وخوارزمية التحكم المنطقي الضبابي(FLC) ، التي تعتمد على الذكاء الاصطناعي وتوفر استجابات أسرع للبيئات المتغيرة. يُحسّن دمج هذه الخوارزميات الأداء العام للنظام من خلال دمج بساطة خوارزميةP&O ، ودقة خوارزميةINC ، وسرعة خوارزميةFLC ، مما يزيد من كفاءة النظام في ظل ظروف بيئية متنوعة.

الكلمات المفتاحية: الأنظمة الكهروضوئية، تتبع نقطة القدرة القصوى(MPPT) ، التوصيل التزايدي(INC) ، وحدة التحكم المنطقي الضبابي(FLC) استخلاص الطاقة، تحسين الكفاءة.

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List of Abbreviations

PV	Photovoltaic
MPP	Maximum power point
MPPT	Maximum power point tracking
P&O	Perturb and observe
INC	Incremental Conductance
FLC	Fuzzy Logic Controller
DC-DC	Continuous-continuous converter
KVL	Kirchhoff's Voltage Law
PWM	Pulse Width Modulation
LED	Light Emitting Diode
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

List of Acronyms

D	The duty cycle
T	The total time period (S)
CH	The chopper
$f_{switching}$	The switching frequency (kHz)
G	The conductance value(1000 W/m^2)
R_{opt}	The optimal value of the load resistance(Ω)
R_c	The load resistance(Ω)
V_{oc}	Open circuit voltage (V)
I_{oc}	Open circuit current(A)
Rs	Series resistance(Ω)
Rsh	Shunt resistance (Ω)

L	Inductance (mH)
C	Capacitance (μF)
I_{sc}	The short circuit current (A)
Pmax	The value of the maximum real power (W)
η	The energy efficiency of the solar cell (%)
$P\gamma$	The incident light power on the surface of the cell
V_L	The voltage across the inductor (V)
W_{on}	The energy input provided by the source to the inductor when CH is on
W_{off}	The energy that the inductor releases to the load when CH is off

General Introduction

General Introduction

Photovoltaic (PV) solar energy is one of the most promising renewable energy sources due to its availability and environmental benefits. However, its efficiency is significantly affected by environmental factors such as solar irradiance and temperature. To ensure maximum power extraction, Maximum Power Point Tracking (MPPT) algorithms are employed to keep the PV system operating at its optimal point. [1]

Among the most commonly used MPPT algorithms are Perturb and Observe (PO), known for its simplicity; Incremental Conductance (INC), which offers higher accuracy; and Fuzzy Logic Control (FLC), which provides flexible and intelligent adaptation to environmental changes. While each method has its strengths, they also have limitations that may affect performance under varying conditions. [2]

This study aims to analyze and compare these algorithms and propose an integrated strategy that combines their advantages to enhance the overall efficiency and reliability of PV systems through more effective MPPT control.

Chapter I

Solar Radiation and Photovoltaic Energy

I.1. Introduction :

1.1. Photovoltaic (PV) Energy as a Sustainable Alternative Photovoltaic (PV) energy is a sustainable energy source that can serve as an alternative to fossil fuels. In this regard, it is considered by researchers to meet future energy needs. Currently, the technology for manufacturing PV modules has greatly improved in terms of quality and manufacturing cost .

1.2.Interest from Political and Scientific Communities These advantages have sparked the interest of the political class and the scientific community to launch and finance numerous research projects in various areas, to promote this field and create new wealth.[1–3].

1.3.Development and Cost Reduction This development is reflected in the reduction of PV module manufacturing costs and research efforts that have promoted power electronics. Consequently, the implementation of PV installations, particularly those of small capacities connected to the Low Voltage (LV) network, has gradually developed.

1.4.Importance of the Inverter in PV Systems Great attention is given to the inverter used in a PV system connected to the electricity distribution network, as its technical properties can influence the quality of electricity production and, consequently, the financial profitability of a PV system [1].

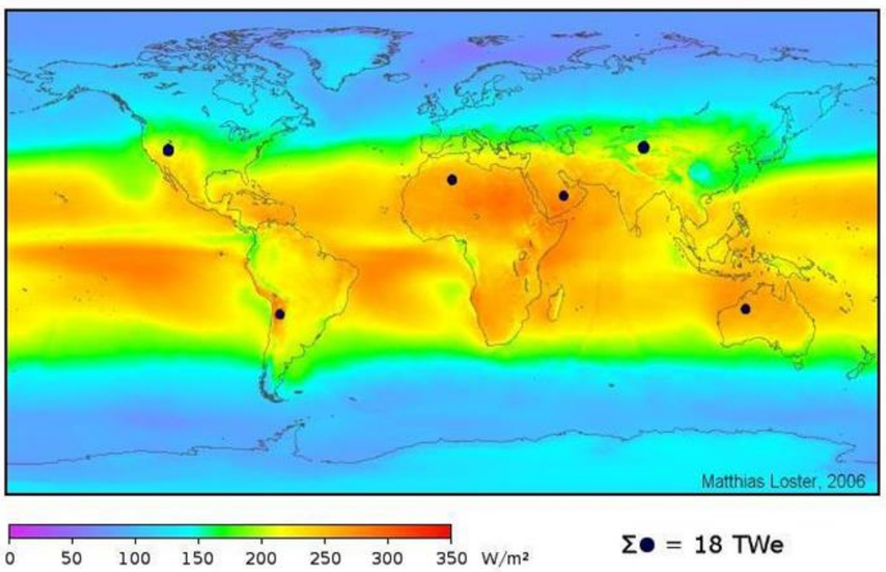

Figure (1.1):gisement solaire dans le monde [1]

Nous pourrions alimenter le monde entier en mettant des panneaux solaires dans les régions ou les points noirs sur la carte.

Figure(1.2):stationsolaired'AinelIbelDjelfad'unecapacitéde20mégawatt et Centrale solaire Ain Skhouna à Saïda d'une capacité 30 MW depuis mai 2016 [1]

I.2. Solar Radiation:

Solar radiation available on the Earth's surface depends on local climatic conditions. Knowledge of the local solar-radiation is essential for the proper design of building energy systems, solar energy systems and a good evaluation of thermal environment within buildings. The best database would be the long-term measured data at the site of the proposed solar system. However, the limited coverage of radiation measuring networks dictates the need for developing solar radiation models. Since the beam component (direct irradiance) is important in designing systems employing solar energy, such as high-temperature heat engines and high-intensity solar cells, emphasis is often put on modelling the beam component[20–22]

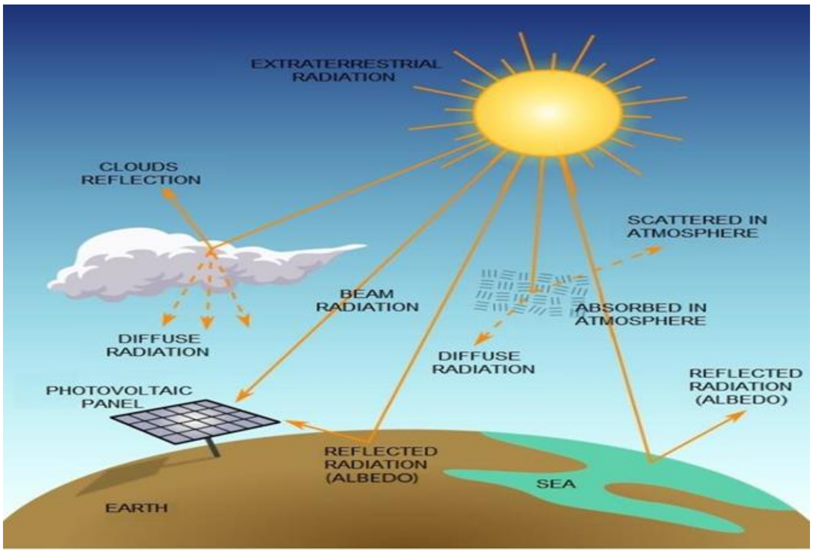

Figure (1.3): Representation of Solar Radiation

I.2.1. Radiation Spectrum:

2.1.1.Definition of the Radiation Spectrum The radiation spectrum refers to the distribution of electromagnetic energy emitted by a source over a wide range of wavelengths. In the case of the sun, solar radiation consists of electromagnetic waves that cover a broad spectrum, including ultraviolet (UV) radiation, visible light, and infrared (IR) radiation.[5–7]

2.1.2. Components of the Solar Radiation Spectrum The solar radiation reaching Earth is divided into three main regions:

1. **Ultraviolet Radiation (UV)**
   - Accounts for approximately 8% of total solar radiation.
   - Has high energy and can be harmful to living organisms.
   - Wavelength range: 100–400 nanometers (nm).
2. **Visible Light**
   - Makes up about 42% of solar radiation.
   - Responsible for natural illumination and color perception.
   - Wavelength range: 400–700 nm, including the seven colors of the spectrum (violet to red).
3. **Infrared Radiation (IR)**
   - Constitutes about 50% of solar radiation.
   - Responsible for transferring heat from the sun to the Earth.
   - Wavelength range: 700 nm to over 1 micrometer.

2.1.3.Importance of the Radiation Spectrum in Photovoltaic Systems Photovoltaic (PV) cells rely on absorbing specific portions of the solar spectrum to convert sunlight into electricity. Most traditional silicon-based solar cells are most efficient in absorbing visible and near-infrared light, while their absorption of ultraviolet radiation is limited due to reflection or absorption by protective layers.

2.1.4.Factors Affecting the Solar Radiation Spectrum The spectrum of solar radiation that reaches the Earth's surface is influenced by several factors:

- The angle of solar radiation incidence, which varies with time and geographical location.
- The atmosphere, which absorbs a portion of ultraviolet radiation.
- Cloud cover and pollution, which reduce the amount of radiation reaching the surface.

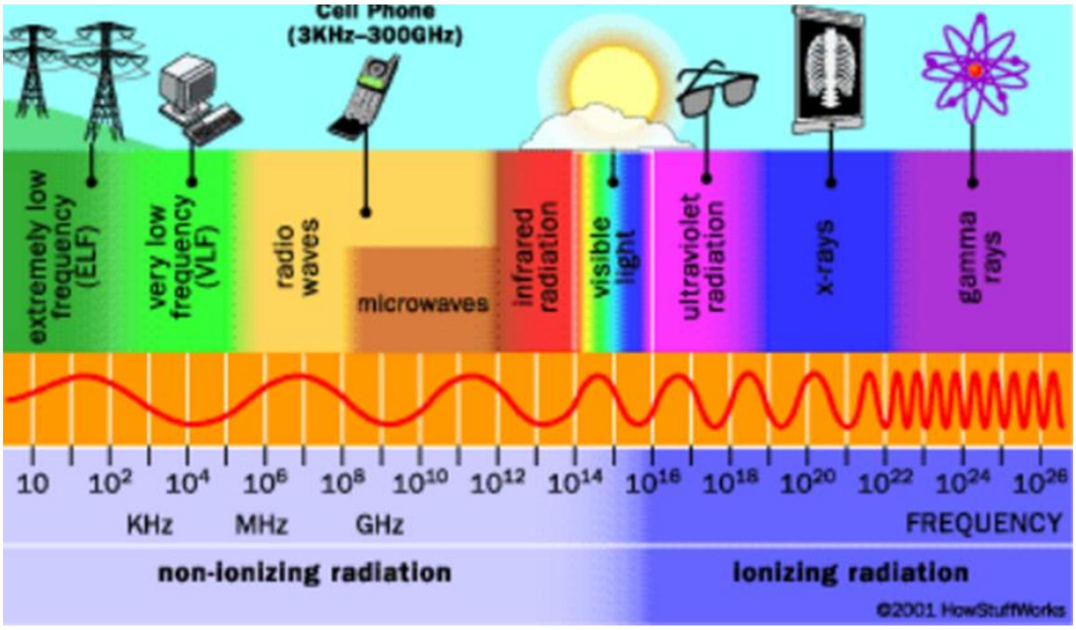

Figure (1.4): Solar Radiation Spectrum

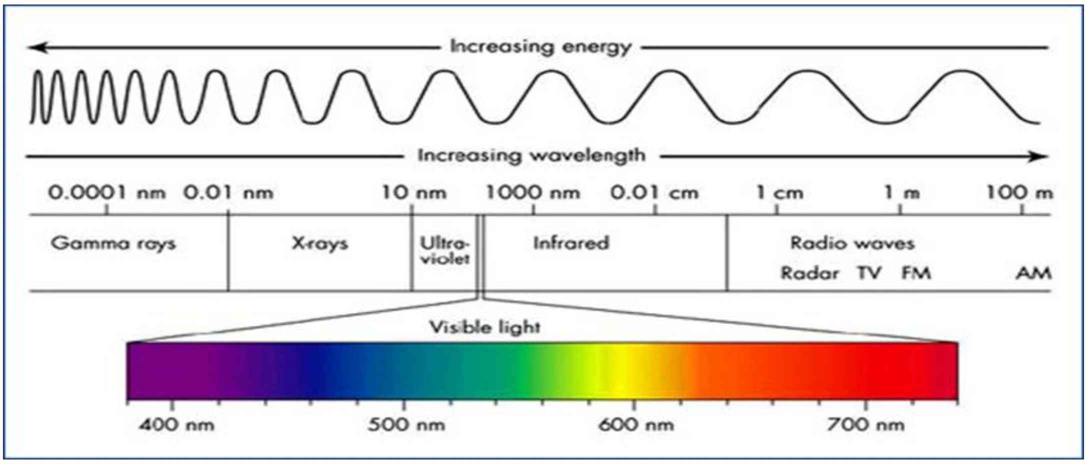

Figure (1.5): Representation of Solar Radiation Spectrum

I.3. Conversion of Solar Radiation by PV Effect:

I.3.1. Basic Composition:

Photovoltaic cells are typically made up of layers of semiconductor materials such as silicon. These cells consist of one layer made of pure material and another layer containing impurities, creating an electron-deficient region (the negative layer) and an electron-rich region (the positive layer).[8–11]

I.3.2. Light Absorption:

When the photovoltaic cell is exposed to sunlight, light photons are absorbed by the silicon material. These photons possess enough energy to excite the electrons within the material.

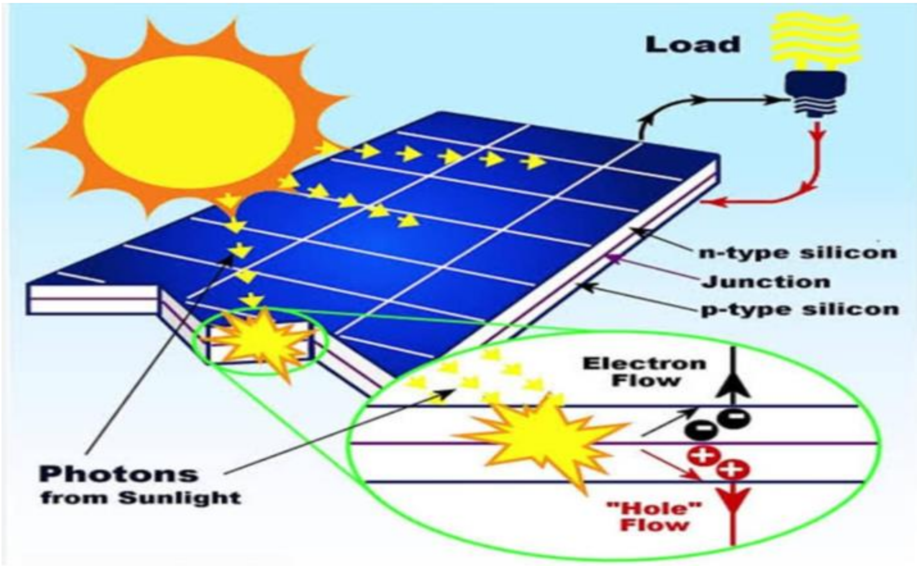

Figure (1.6): Solar Radiation Conversion by PV Effect

I.4. Photovoltaic Generator:

4.1.Dynamic Terminal Characteristics of a Photovoltaic Generator: This paper investigates the dynamic properties of PV generators, especially from the point of view of the interfacing devices used between the PV generators and the loads. You can find it here.[4]

4.2.Photovoltaic Generator as an Input Source for Power Electronic Converters: This paper defines the most important properties an input source should have to emulate a real PV generator and qualifies two commercial solar array simulators. You can access it here.

4.3.Comprehensive Dynamic Analysis of Photovoltaic Generator Interfacing DC-DC Boost Power Stage: This study reveals the dynamics of PV generator interfacing DC-DC boost power stage. You can read more about it here.

4.4.N8900APV Series Photovoltaic Array Simulators: This product from Keysight provides a comprehensive solution for testing solar array inverters. More details can be found here.

4.5.Solar Array Simulators by REGATRON: REGATRON offers precise and fast solar array curve computation for in-depth testing of solar inverters. You can explore their products here.

4.6.Solar Array Simulator DC Power Supply by Chroma: Chroma provides programmable IV curve simulation with fast transient response for MPPT performance evaluation on PV inverter devices. More information is available here.

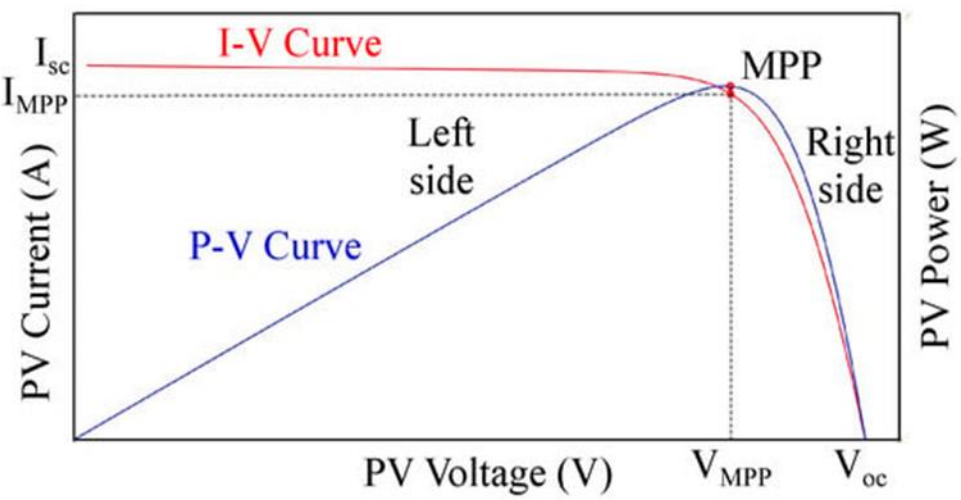

Figure (1.7): Typical Characteristics of a PV Generator

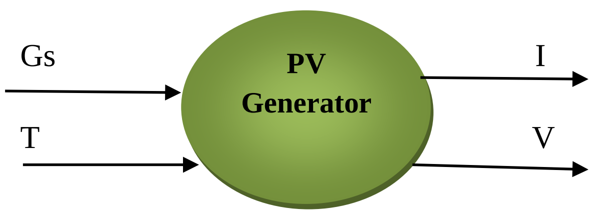

Figure (1.8):Block Diagram of a PV Generator

I.4.1. photovoltaic cell :

A solar cell is a photosensitive semiconductor device composed of thin layers. When exposed to incident solar electromagnetic radiation, it generates electricity through the photovoltaic effect. When sunlight strikes the PV cell, charge carriers areproduced, leading to an electric current if the circuit is closed.[12]

These charges are generated when the energy of the incident photon exceeds the bandgap energy, allowing it to dislodge a covalent electron from the semiconductor. This process creates an internal electric field, which facilitates the separation of oppositely charged carriers. The movement of these charge carriers results in the generation of a current, known as the photocurrent.

Figure (1.9): photovoltaic cell

Due to its inherent characteristics, a PV cell exhibits nonlinear behavior and can be modeled as a combination of a current source in parallel with an ideal diode.

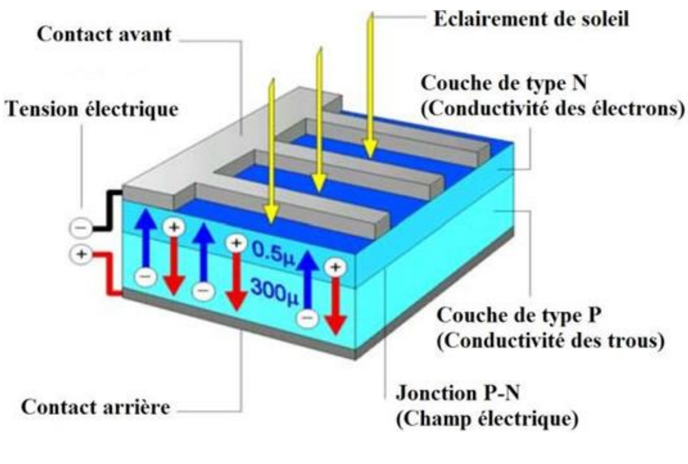

Figure (1.10): Structured’unecellule PV

I.4.2. Modelling of a PV Cell:

The basic equation (1) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array because they are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation and achieve the modified Eq 2, where Ipv and I0 are the photovoltaic and saturation currents of the array and Vt = Ns*k*T/q is the thermal voltage of the array with Ns cells connected in series. If the array is composed of Np parallel connections of cells the photovoltaic and saturation currents may be expressed as: Ipv=Ipv,cell * Np, I0=I0,cell * Np. Rs is the equivalent series resistance of the array and Rp is the equivalent parallel resistance. This equation originates the I-V curve seen in Fig. 5, where short circuit (0, Isc), maximum power point (Vmpp, Impp) and open-circuit (Voc, 0) are highlighted. This Eq 2 is for Single Mode diode operation. In Double diode model an extra diode attached in parallel to the circuit of single diode model. This diode is included to provide an even more accurate I-V characteristic curve that considers for the difference in flow of current at low current values due to charge recombination in the semiconductor's depletion region.[13–15]

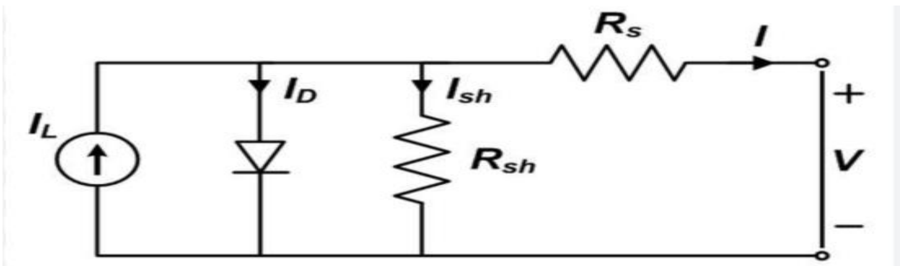

Figure (1.11): Equivalent Circuit of a PV Cell

I.4.3. Types of Photovoltaic Cells :

Photovoltaic cells are made of semiconductors based on silicon (Si), germanium (Ge), selenium (Se), cadmium sulfide (CdS), cadmium telluride (CdTe), or gallium arsenide (GaAs). However, silicon is currently the most widely used material for making photovoltaic cells.[1–3]

b. **Semiconductor Materials**

A semiconductor is a material that has the electrical characteristics of an insulator, but for which the probability of an electron contributing to an electric current, although low, is significant enough.

This is possible due to a large area p-n junction. This junction designates a region of the crystal where doping abruptly varies from p-type to n-type, where electron-hole pairs created by light are separated by the electric field of the junction.

Semiconductors are crucial in electronics because they offer the ability to control, by various means, both the amount of electric current that can pass through them and the direction the current can take.

c. **Structure and Description of the Photovoltaic Junction**

A P-doped semiconductor crystal is covered by a very thin N-doped layer with a thickness of a few thousandths of a millimeter. Between the two regions is a junction J. The N-region is covered by a metal grid that serves as the cathode (k), while on the other side a metal plate acts as the anode. The total thickness of the crystal is about a millimeter. These cells are fragile, so they are encased in a layer of glass that is shock and weather-resistant and sometimes covered with an anti-reflective layer. In the classic architecture of a cell, charge collectors are added through screen printing techniques, which involve adding a metallic paste (according to a defined pattern) that is then solidified during another pass through a furnace.

On the p-layer at the back, a positive electrode, usually made of aluminum or silver, is deposited on a substrate. This metallization completes the fabrication of the cells.

d. **The p-n Junction**

When these types of p and n semiconductors come into contact at the junction line, electrons diffuse from the n-side to the p-side.

They will also combine with holes, creating fixed negative ions on the p-side and leaving fixed positive ions on the n-side.

As a result, equilibrium is reached without further diffusion. The junction at the diode is divided into two regions: the depletion region and the quasi-neutral region. Figure 1 shows the diffusion and depletion layer where the depletion region contains the junction.

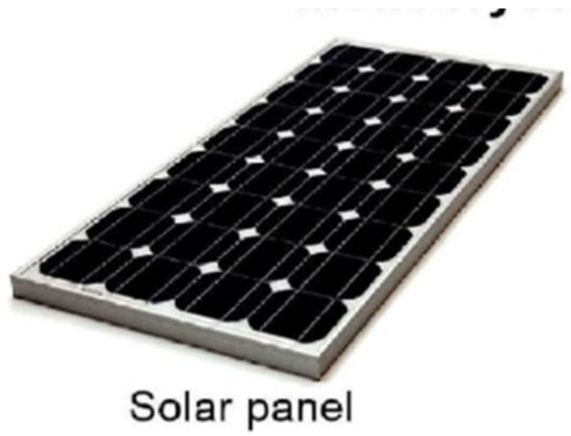

Figure (1.12): Monocrystalline Cells

Figure (1.13): Polycrystalline Cells.

I.5. The Impact of Temperature on Solar Panel:

I.5.1. 1. Efficiency Decrease

As the temperature rises, the efficiency of solar panels tends to decrease. This is because higher temperatures increase the electrical resistance within the solar cells, reducing their ability to convert sunlight into electricity.

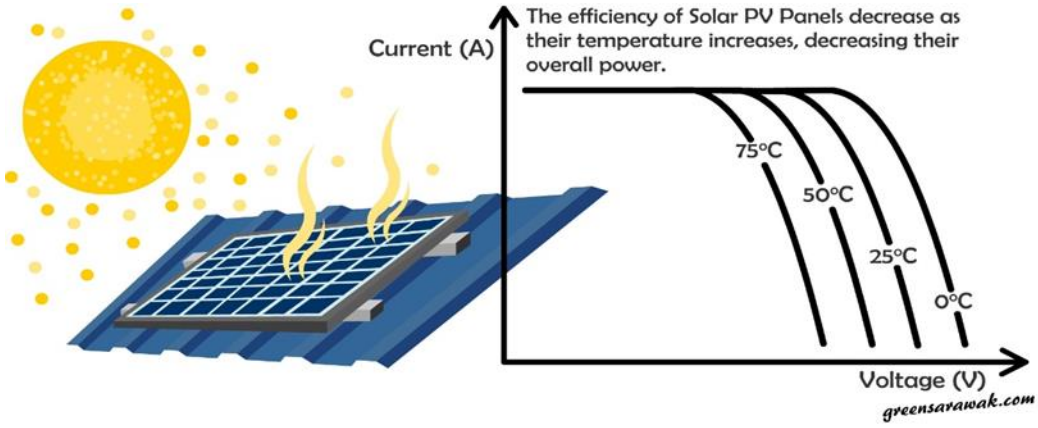

Figure (1.14): The Impact of Temperature on Solar Panel

I.5.2. 2. Optimal Temperature Range

Solar panels operate most efficiently within an optimal temperature range, typically around 25°C (77°F). Beyond this range, their performance can decline.

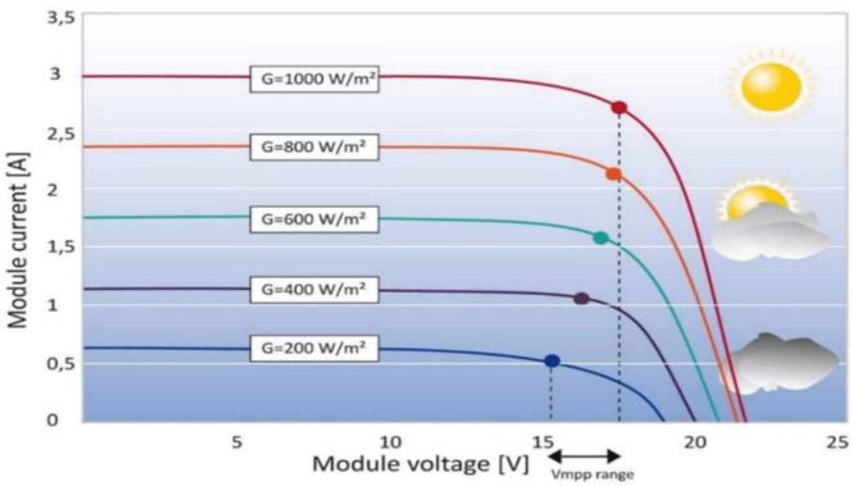

Figure (1.15): Optimal Temperature Range

I.5.3. 3. Voltage Drop

Higher temperatures can cause a drop in the open-circuit voltage of solar cells, leading to a decrease in overall power output.

I.5.4. 4. Mitigation Strategies

To mitigate the effects of high temperatures, solar panels can be installed with proper ventilation and cooling systems. Additionally, choosing panels with a lower temperature coefficient can help maintain efficiency in hotter climates

Figure (1.16): Key Factors Leading to Solar Panel Degradation

I.6. applications of solar radiation and photovoltaic energy: [16–19].

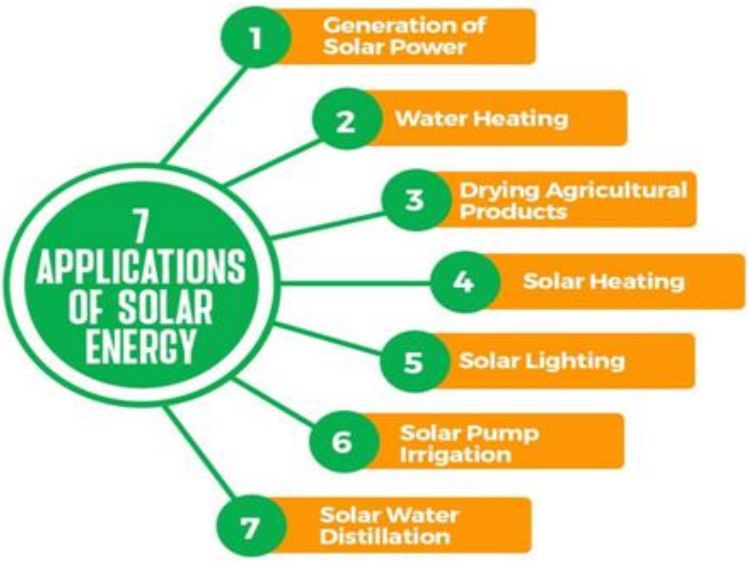

Figure (1.16):applications of solar energy

Electricity Generation:

Solar panels convert solar radiation into electricity using photovoltaic cells. These panels can be installed on rooftops or in solar farms to produce electricity for homes, factories, and cities.

Water Heating:

Solar thermal systems use solar radiation to heat water. These systems can provide hot water for homes and industrial facilities.

Concentrated Solar Power (CSP):

CSP technology uses mirrors or lenses to concentrate solar radiation onto a small area, producing high temperatures that are used to generate electricity through steam turbines.

Powering Small Devices:

Photovoltaic cells can be used to power small devices such as calculators, watches, and electronic toys.

Street Lighting:

Solar-powered street lights provide illumination in areas that are far from electrical grids, helping to reduce traditional electricity consumption.

Water Pumping:

Solar water pumps are used in rural areas to pump water from wells, providing drinking water and irrigation.

I.7. Advantages and Disadvantages of PV Energy:

I.7.1. Advantages:

- **Renewable Energy Source:** PV systems use sunlight, which is an abundant and renewable resource.
- **Environmentally Friendly:** PV systems generate electricity without emitting harmful pollutants or greenhouse gases.

- **Low Operating Costs:** Once installed, PV systems have low maintenance and operating costs.
- **Energy Independence:** PV systems can reduce dependence on fossil fuels and increase energy security.
- **Scalability:** PV systems can be scaled to meet different energy needs, from small residential setups to large solar farms

I.7.2. Disadvantages:

- **High Initial Costs:** The installation of PV systems can be expensive, although costs have been decreasing over time.
- **Weather Dependent:** The efficiency of PV systems can be affected by weather conditions, such as cloudy or rainy days.
- **Energy Storage:** Storing excess energy generated by PV systems can be challenging and may require additional investment in batteries.
- **Space Requirements:** PV systems require a significant amount of space for installation, which can be a limitation in urban areas.
- **Efficiency:** The efficiency of PV systems is relatively low compared to some other energy sources, and improvements are still needed.

I.8. Conclusion:

solar radiation and photovoltaic energy present a bright future for renewable and sustainable energy.

The ability to convert abundant sunlight into electrical and thermal energy opens up vast possibilities for meeting our daily needs and reducing our reliance on traditional energy sources that contribute to environmental pollution and the depletion of natural resources.

From generating electricity to heating water and powering small devices, solar technology demonstrates multiple possibilities for enhancing the quality of life and achieving sustainable development.

With continuous scientific and technological advancements, we have the opportunity to build a world that relies more on clean and renewable energy, contributing to environmental protection and ensuring a more sustainable future for generations to come.

Chapter II

DC-DC Converter

II.1. Introduction :

DC-DC converters constitute fundamental electronic circuits that play a pivotal role in contemporary power management systems. Their primary function is to modify the voltage level of a direct current (DC) source, ensuring stable and efficient power delivery to a wide range of electronic devices and systems. In scenarios where input voltage levels are subject to fluctuations due to factors such as battery discharge over time or variations in load conditions, DC-DC converters regulate the output voltage, thereby ensuring reliable power supply to system components. A key advantage of DC-DC converters is their high power conversion efficiency. By employing switching techniques, these converters effectively mitigate power losses associated with resistive elements, such as transformers or linear regulators, which typically generate heat and dissipate energy. Consequently, this enhances overall efficiency and extends battery life in portable electronic devices. Furthermore, DC-DC converters provide the flexibility to either step up or step down voltage levels, facilitating efficient power distribution in electronic systems. Additionally, they can offer galvanic isolation, which separates input and output grounds to mitigate the risk of ground loops and protect sensitive components from voltage spikes and electrical noise.

II.2. DC-DC Converters:

DC-DC converters are static power conversion devices that operate using a direct current (DC) voltage source and generate a controllable DC output voltage across a load.

These converters can be designed utilizing thyristors for high-power applications, reaching several hundred megawatts (MW), with a chopping frequency in the range of a few kilohertz (kHz). Alternatively, for lower power applications—ranging from several hundred kilowatts (kW) up to approximately 100 kW—DC-DC converters can be implemented using transistors, enabling higher chopping frequencies of up to 100 kHz.

The following figure illustrates the symbol of a DC-DC converter.

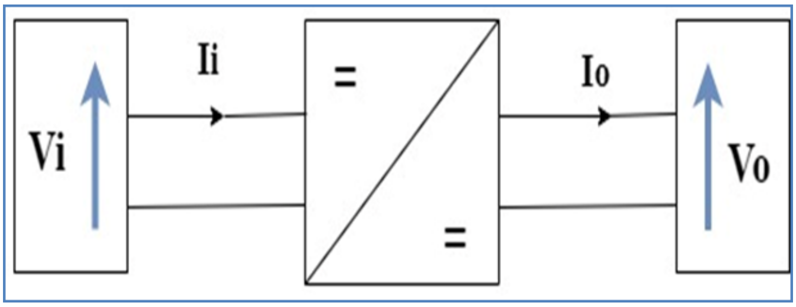

Figure (II.1): DC-DC Converters

II.3. Applications of DC-DC Converter:

For several years, switch-mode power converters have been extensively utilized in modern electronics across various sectors, including industrial, commercial, utility, and consumer markets. In low-power DC-DC conversion applications, the predominant power conversion methods are based on three primary topologies: buck, boost, and buck-boost converters. However, specialized applications often require advanced configurations or modified variations of these conventional topologies to meet specific operational demands.

The literature presents numerous DC-DC converter types; however, no single solution is universally applicable to all scenarios. In general, power conversion techniques have been widely implemented across industrial sectors, research and development, and everyday applications. DC-DC converters represent a fundamental area of study in power electronics and energy drives due to their extensive integration into industrial systems. Several of these applications are depicted in Figure (II.2).

High-voltage gain converters are employed in various advanced applications, including radar systems, DC distribution networks, data centers, and renewable energy systems. Their role is particularly crucial in renewable energy applications, where high-voltage gain DC-DC converters enable voltage amplification, ensuring compatibility with distribution systems. DC distribution, in general, offers multiple advantages, including a reduced number of conversion stages, lower costs, and improved power quality, making it a preferred choice for a wide range of applications

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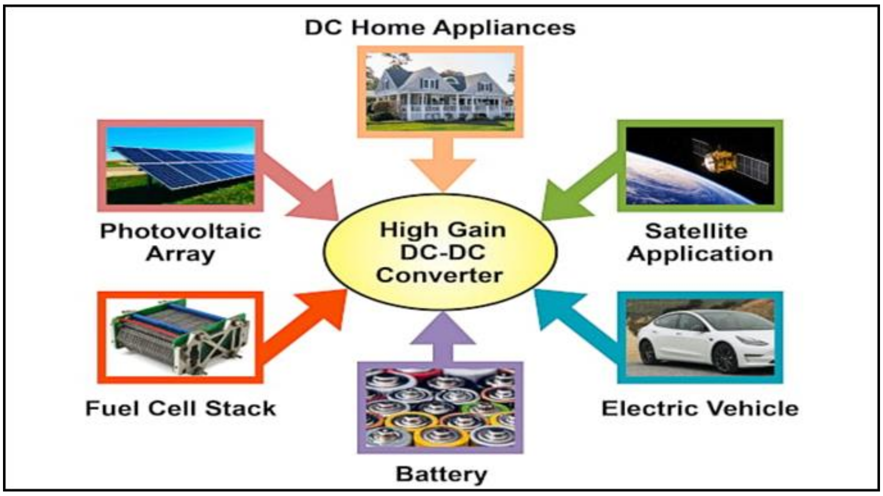

Figure (II.2): Applications of DC/DC Converters.

Here are some of DC-DC converter applications:

- **Renewable energy applications:** DC-DC converters utilized in renewable energy applications must be capable of drawing a continuous and smooth input current to minimize ripple. Additionally, they should possess the capability to integrate with various power sources effectively. Non-isolated interleaved high-voltage gain converters are commonly employed for interfacing renewable energy systems with microgrids[6]**.**
- **Medical devices:** Isolated DC-DC converters are essential in applications where safety is a primary concern, as they ensure the separation of the output from potentially hazardous voltages on the input side. Conversely, non-isolated converter topologies can be utilized in applications such as the power supply for X-ray systems.
- **Vehicles:** In automotive applications, the primary DC-DC converter converts power from the onboard high-voltage battery into lower DC voltage levels required to operate various electrical components, such as lighting systems, windshield wipers, and window controls [7]. This function is essential for both electric and hybrid electric vehicles. Isolation is particularly critical in scenarios where the separation of control systems from high-voltage domains is necessary. Buck-boost converters are employed for voltage step-up or step-down operations, while charge-pump converters are utilized for voltage inversion.

- **Smart lighting:** Various lighting applications necessitate LED backlight driver solutions that exhibit high efficiency, precise direct current control, voltage protection, pulse-width modulation (PWM)-based regulation, and a simplified design. DC-DC converter topologies that function effectively as LED drivers include linear regulators, charge pumps, and other conventional switching converters.

II.4. Types of DC-DC converters:

There are three types of DC-DC converters, namely: Buck, Boost, and Buck-Boost.

II.4.1. Buck Converter:

A buck converter is a type of DC-DC converter specifically designed to perform step-down conversion of the applied DC input signal. In the operation of buck converters, a fixed DC input voltage is transformed into a lower-magnitude DC output voltage. This implies that the converter is engineered to generate an output DC signal with a reduced voltage level compared to the input. It is also referred to as a Step-Down DC-DC Converter, Step-Down Chopper, or Buck Regulator.

Operating Principle of Buck Converter

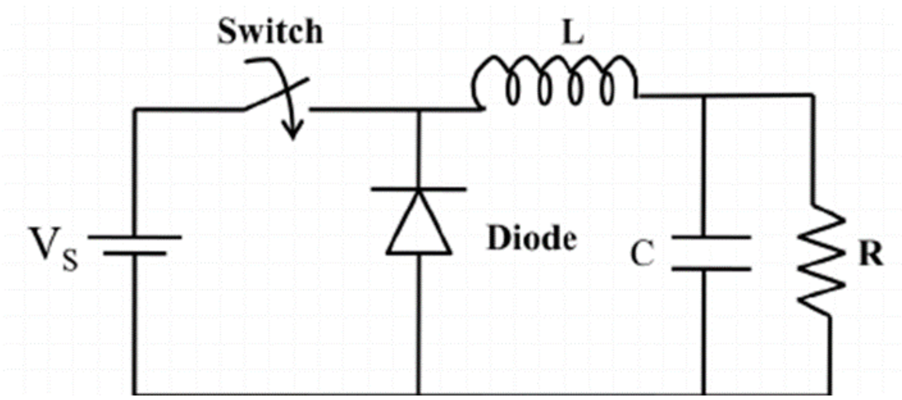

Figure (II.3): The Circuit Representation of Buck Converter

In the figure above, it is evident that, in addition to the power electronics solid-state device functioning as a switch within the circuit, a freewheeling diode is also present as a secondary switching component. The combination of these two switching elements is integrated with a low-pass LC filter to mitigate current and voltage ripples, thereby facilitating the generation of a regulated DC output. A pure resistive load is connected across the entire configuration, serving as the circuit's load element.

The whole operation of the circuit takes place in two modes. The first mode is the one when the power MOSFET i.e., switch S_1 is closed.

In this mode of operation, switch S_1 is in closed condition thus allows the flow of current to take place through it.

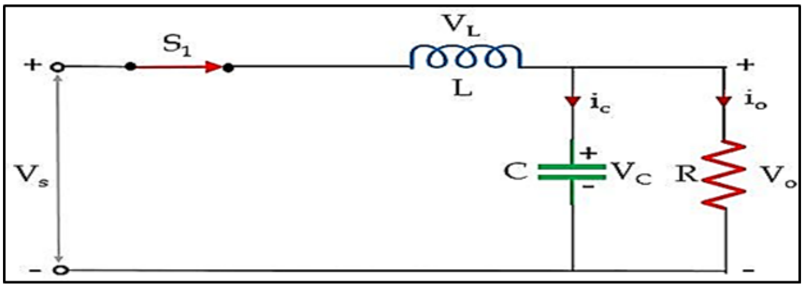

Figure (II.4): Buck Converter When S_1 is Closed

When a fixed DC voltage is initially applied to the circuit's input terminals, and switch S1 is in the closed position, current flows through the circuit as illustrated above. As a result of this current flow, the inductor within the circuit stores energy in the form of a magnetic field. Additionally, the presence of a capacitor allows current to flow through it, leading to the accumulation of charge, with the voltage across the capacitor appearing across the load.

However, in accordance with Lenz’s law, the energy stored within the inductor opposes the change that generated it. Consequently, an induced current is produced, leading to a reversal in the polarity across the inductor.

Here the total time period is a combination of T_{on} and T_{off} time.

$$T = T_{on} + T_{off} \tag{II.1}$$

The duty cycle is written as:

$$D = \frac{T_{on}}{T} \tag{II.2}$$

On applying KVL, in the above-given circuit

$$V_s = V_L + V_{\mathrm{out}} \quad (\mathrm{II.3})$$

$$V_L = V_s - V_{\mathrm{out}} \quad (\mathrm{II.4})$$

Also,

$$V_L = L\frac{di_L}{dt} = V_s - V_{\mathrm{out}} \quad (\mathrm{II.5})$$

$$\frac{di_L}{dt} = \frac{V_s - V_{out}}{L} \quad (\mathrm{II.6})$$

When S1 is in closed condition then T_{on} = DT thus Δt = DT. Therefore, we can write

$$\frac{\Delta i_L}{\Delta t} = \frac{V_s - V_{\mathrm{out}}}{L} \quad (\mathrm{II.7})$$

$$\frac{\Delta i_L}{DT} = \frac{V_s - V_{\mathrm{out}}}{L} \quad (\mathrm{II.8})$$

Hence,

$$\Delta i_t = \left(\frac{V_s - V_{\mathrm{out}}}{L}\right) DT \quad (\mathrm{II.9})$$

The above equation represents the change in current through the circuit when switch S1 is closed.

Now, the second mode of operation takes place when switch S_2 is closed and S_1 gets open. However, you must be thinking about how automatically, the switch S_2 will be closed. So, as we have discussed that the inductor in the circuit will store the energy so, once S_1 will get open the inductor in the circuit will start acting as the source. In this mode, the inductor releases the energy which is stored in the previous mode of operation. As we have discussed that the polarity of the inductor will get reversed therefore this causes the freewheeling diode to come in a forward-biased state which was earlier present in a reverse-biased state due to the applied dc input.

Due to this, the flow of current takes place in a way as shown below:

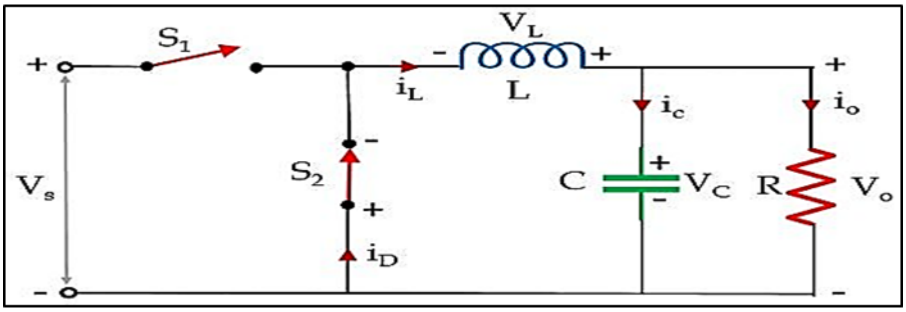

Figure (II.5): Buck ConverterWhen S_2 is Closed

This flow of current will take place till the time the stored energy within the inductor gets completely collapsed. As once the inductor gets completely discharged, the diode comes in reverse biased condition leading to cause opening of switch S_2, and instantly switch S_1 will get closed and the cycle continues.

Now, let us apply KVL, in the above circuit

$$0 = V_L + V_{\text{out}} \tag{II. 10}$$

$$V_L = L\frac{di_L}{dt} = -V_{\text{out}} \tag{II. 11}$$

Since, we know,

$$\text{T} = \text{T}_{\text{on}} + \text{T}_{\text{off}} \tag{II. 12}$$

$$\text{T} = \text{DT} + \text{T}_{\text{off}} \tag{II. 13}$$

$$\text{T}_{\text{off}} = \text{T} - \text{DT} \tag{II. 14}$$

$$\text{T}_{\text{off}} = (1 - \text{D})\text{T} \tag{II. 15}$$

$$V_L = L\frac{\Delta i_L}{\Delta t} = -V_{\text{out}} \tag{II. 16}$$

$$\text{T}_{\text{off}} = \Delta\text{t} = (1 - \text{D})\text{T} \tag{II. 17}$$

$$L\frac{\Delta i_L}{(1 - D)T} = -V_{\text{out}} \tag{II. 18}$$

So,

$$\Delta i_L = -\frac{V_{\text{out}}}{L}(1-D)T \qquad (II.19)$$

This equation represents the rate of change in current through the inductor when the switch S1 is open.

As we know that the net change of current through the inductor in one complete cycle is zero. Thus,

$$\Delta i_{L_{(s1-closed)}} + \Delta i_{L(S1-\text{ open })} = 0 \qquad (II.20)$$

$$\frac{V_s - V_{\text{out}}}{L}DT + \left\{-\frac{V_{\text{out}}}{L}(1-D)T\right\} = 0 \qquad (II.21)$$

On simplifying,

$$\frac{V_s DT}{L} - \frac{V_{\text{out}}\,DT}{L} - \frac{V_{\text{out}}\,T}{L} + \frac{V_{\text{out}}\,DT}{L} = 0 \qquad (II.22)$$

$$\left(\frac{V_s DT}{L}\right) = \frac{V_{\text{out}}\,T}{L} \qquad (II.23)$$

$$V_{\text{out}} = DV_s \qquad (II.24)$$

The figure given below represents the waveform representation of Buck Converter:

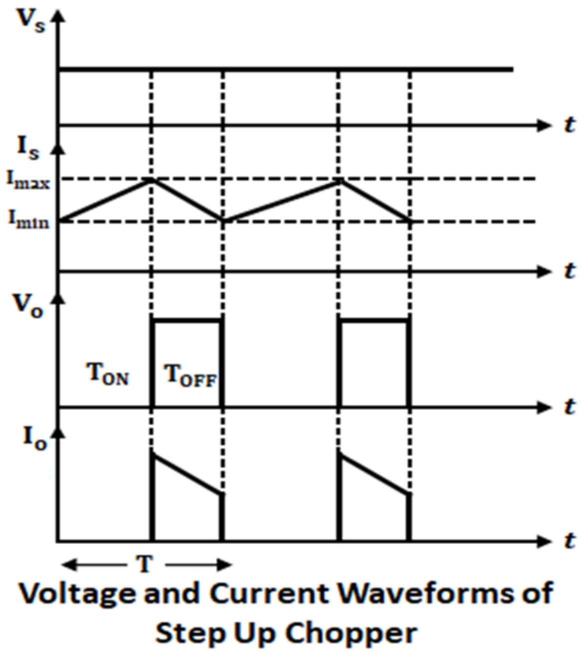

Figure (II.6): Waveform Representation

Hence, we can say, buck converters are used to provide a lower value of dc signal from a fixed dc input.

II.4.2. Boost Converter:

Boost converters, also referred to as step-up DC-DC converters, are a type of chopper circuit designed to generate an output voltage that exceeds the supplied input voltage. In boost converters, DC-DC conversion occurs in such a manner that the circuit delivers an output voltage of greater magnitude than the input voltage. The term "boost" is attributed to this converter due to its ability to elevate the output voltage above the input voltage level.

Operating Principle of Boost Converter

The figure given below is the circuit representation of the boost converter:

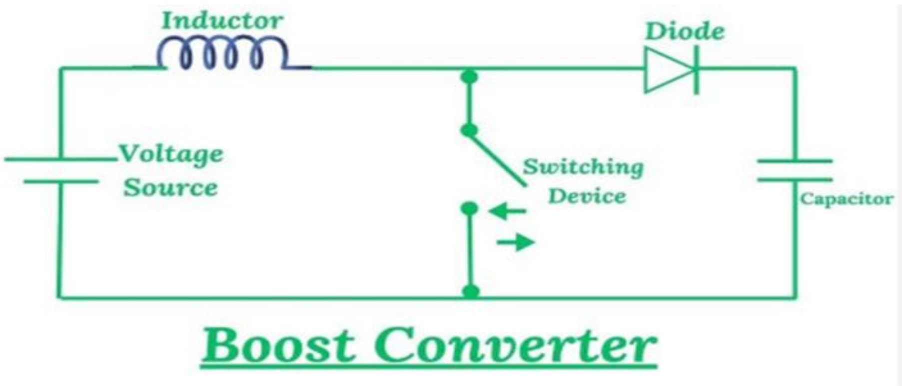

Figure (II.7): Elementary Circuit of Boost Converter

The circuit here is an elementary form of step-up DC-DC converter which necessarily requires a large inductor L in series connection with the voltage source. The whole circuit arrangement operates in a way that it helps in maintaining a regulated dc signal at the output.

Let us understand how the given circuit operates in order to provide an increased dc signal at the load.

Initially, when the chopper CH is in on state, then in the presence of supply dc input current begins to flow through the closed path of the circuit i.e., passing through the inductor as shown in the figure below.

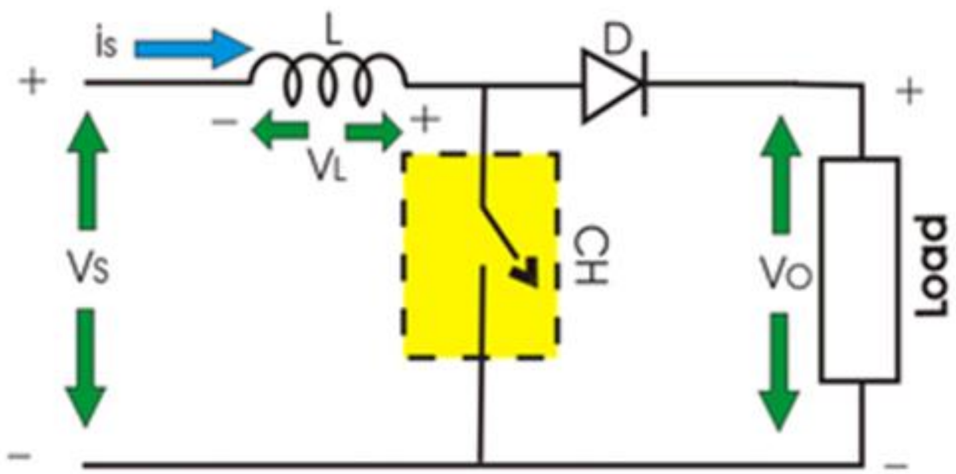

Figure (II.8): The Chopper CH is in on State

Here, the polarity of the inductor will be according to the direction of the flow of current. In this particular case, the diode in the configuration is in reverse biased condition and so current will not be allowed to flow through that particular part of the circuit during on state of the DC-DC converter. Resultantly, the voltage across DC-DC converter will appear across the load.

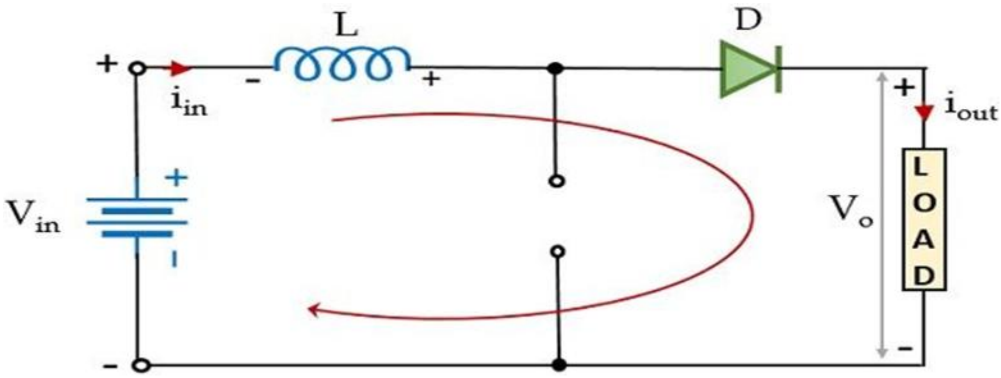

Figure (II.9): The Chopper CH is in OffState

Furthermore, at the instant when CH is in the off state, then the part of the circuit through which the current was flowing earlier will not be active in this case. However, as the inductor stores, the energy in the form of a magnetic field and so the current through it will not die out instantly.

Also, we know according to Lenz’s law a reverse current will be induced that will oppose the cause which has produced it. And so, due to the induced current, the polarity of the inductor will get reversed. This reverse polarity of the inductor forward biases the diode present in the circuit. This provides the path for the current through the diode that flows through the load during the off state of the chopper i.e., T_{off}. However, we must note here that the current through the inductor is of decreasing nature and will die out after a point in time.

Thus, the total voltage across the load will be given as:

$$V_{\text{out}} = V_{\text{in}} + V_L \text{(II.25)}$$

This means that the output voltage exceeds the applied input voltage. Thus, performs step-up conversion as the energy stored within the inductor during the T_{on} period is released during the T_{off} period.

During the T_{on} period, the voltage across the inductor will be given as:

$$V_L = L\frac{di}{dt} \qquad \text{(II.26)}$$

Let us have a look at the waveform representation of the step-up choppershownbelow:

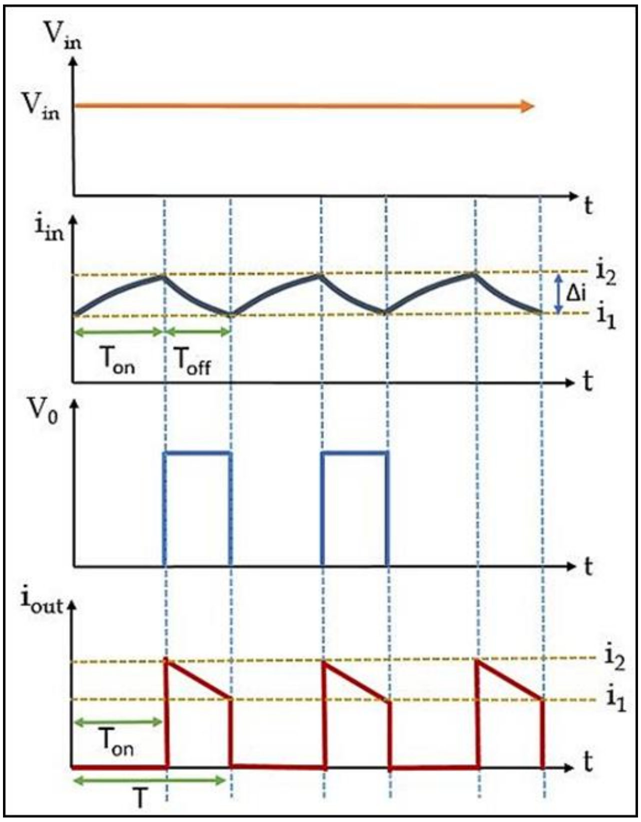

Figure (II.10): Waveform Representation

During the T_{on} period, the current through the inductor will change from i_1 to i_2 this is clearly shown above. While during the T_{off} period, the inductor current will change from i_2 to i_1. Now, talking about voltage, so during the turn-on period, the voltage across the inductor will be equal to the supply input voltage. But when CH gets off then on applying KVL in the figure shown above, we will get,

$$V_L - V_0 + V_{in} = 0 \qquad (II.27)$$

This means,

$$V_L = V_0 - V_{in} \qquad (II.28)$$

Considering that output current is varying linearly, the energy input provided by the source to the inductor, when CH is on, is given as:

$$W_{on} = (\text{voltage across the inductor})(\text{ average current through the inductor})T_{on}$$

$$W_{on} = V_{in}\left(\frac{i_1 + i_2}{2}\right)T_{on} \qquad (II.29)$$

Further, the energy that the inductor releases to the load when CH is off is given as:

$$W_{off} = (\text{voltage across the inductor}) (\text{average current through the inductor})\ T_{off}$$

$$W_{off} = V_{out} - V_{in}\left(\frac{i_1 + i_2}{2}\right)T_{off} \qquad (II.30)$$

For a lossless system, comparing the two energies, we will have,

$$V_{in}\left(\frac{i_1 + i_2}{2}\right)T_{on} = V_{out} - V_{in}\left(\frac{i_1 + i_2}{2}\right)T_{off} \qquad (II.31)$$

On simplifying,

$$V_{in}\,T_{on} = V_{out}\,T_{off} - V_{in}\,T_{off} \qquad (II.32)$$

$$V_{out}\,T_{off} = V_{in}\,T_{on} + V_{in}\,T_{off} \qquad (II.33)$$

$$V_{out}\,T_{off} = V_{in}\,(T_{on} + T_{off}) \qquad (II.34)$$

Since we know, $T = T_{on} + T_{off}$, therefore,

$$V_{out}\,T_{off} = V_{in}\,T \tag{II.35}$$

$$V_{out} = V_{in}\,\frac{T}{T_{off}} \tag{II.36}$$

$$V_{out} = V_{in}\,\frac{T}{T - T_{on}} \tag{II.37}$$

$$V_{out} = V_{in}\,\frac{1}{\left(\frac{T}{T} - \frac{T_{on}}{T}\right)} \tag{II.38}$$

Since, we know, duty cycle i.e., $\alpha = T_{on}/ T$

$$V_{0ut} = V_{in}\,\frac{1}{(1 - \alpha)} \tag{II.39}$$

Thus, we can conclude here that the average load voltage can be stepped up with the change in the duty cycle.

II.4.3. Buck-Boost Converter:

The buck-boost converter is a type of DC-DC converter capable of producing an output voltage magnitude that can be either greater or lesser than the input voltage magnitude. It is utilized to "step up" DC voltage, analogous to the function of a transformer in AC circuits. The buck-boost converter is equivalent to a flyback converter; however, it employs a single inductor instead of a transformer.

Two distinct types of DC-DC converters are commonly referred to as buck-boost converters, which belong to the broader category of chopper circuits. The buck-boost converter is particularly versatile, as it can operate as either a step-down or step-up converter depending on its duty cycle, denoted as DDD. A typical buck-boost converter circuit is illustrated below:

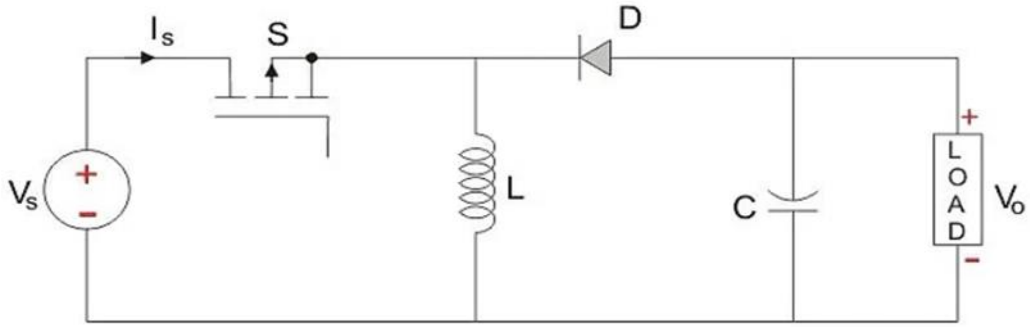

Figure (II.11): The Circuit Representation of Buck-Boost Converter

The input voltage sourceis connected to a solid-state device. The second switch used is a diode. The diode is connected, in reverse to the direction of power flow from source,

to a capacitor and the load and the two are connected in parallel as shown in the figure above.

The controlled switch in the converter uses Pulse Width Modulation (PWM) to toggle on and off. PWM may operate based on time or frequency, with time-based being the more common approach.

Frequency-based modulation, though versatile, has the disadvantage of requiring a wide range of frequencies to precisely control the switch and thus achieve the desired output voltage.

Time based Modulation is mostly usedforDC-DC converters. It is simple to construct and use.

The frequency remains constant in this type of PWM modulation. The Buck Boost converter has two modes of operation. The first mode is when the switch is on and conducting.

Mode I: Switch is ON, Diode is OFF

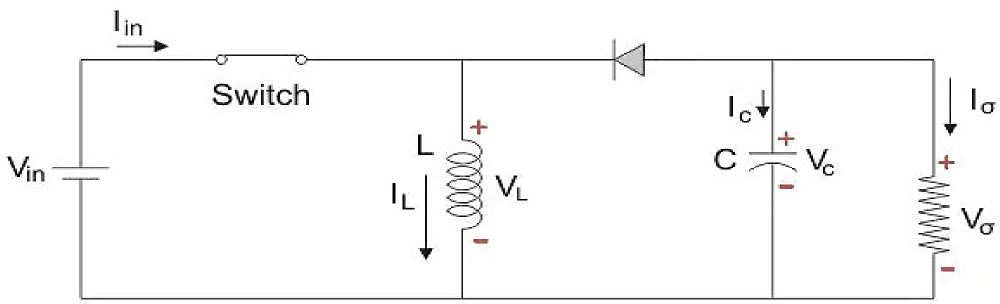

Figure (II.12): The Equivalent Circuit of Mode I

The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and the inductor and back to the DC input source.

The inductor stores charge during the time the switch is ON and when the solid state switch is OFF the polarity of the Inductor reverses so that current flows through the load and through the diode and back to the inductor. So, the direction of current through the inductor remains the same.

Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF}.

We define the time period, T, as:

$$T = T_{ON} + T_{OFF} \quad (II.40)$$

and the switching frequency:

$$f_{\text{switching}} = \frac{1}{T} \quad (II.41)$$

Let us now define another term, the duty cycle:

$$D = \frac{T_{ON}}{T} \quad (II.42)$$

Let us analyse the Buck Boost converter in steady state operation for this mode using KVL.

$$V_{in} = V_L$$
$$V_L = L\frac{di_L}{dt} = V_{in} \qquad (II.43)$$
$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{\text{in}}}{L}$$

Since the switch is closed for a time T_{ON} = DT we can say that Δt = DT.

$$(\Delta i_L)_{\text{closed}} = \left(\frac{V_{in}}{L}\right)DT \qquad (II.44)$$

While performing the analysis of the Buck-Boost converter we have to keep in mind that

- The inductor current is continuous and this is made possible by selecting an appropriate value of L.
- The inductor current in steady state rises from a value with a positive slope to a maximum value during the ON state and then drops back down to the initial value with a negative slope. Therefore, the net change of the inductor current over any one complete cycle is zero.

Mode II:<u>Switch is OFF, Diode is ON</u>

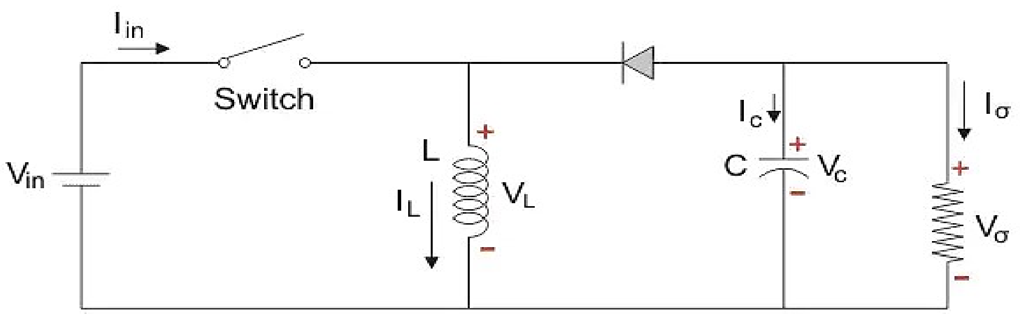

Figure (II.13): The Equivalent Circuit of Mode II

In this mode the polarity of the inductor is reversed and the energy stored in the inductor is released and is ultimately dissipated in the load resistance and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source. But for analysis we keep the original conventions to analyse the circuit using KVL.

Buck Boost Converter Formula

Let us now analyse the Buck Boost converter in steady state operation for Mode II using KVL.

$$V_L = V_o \tag{II.45}$$

$$V_L = L\frac{di_L}{dt} = V_o \tag{II.46}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L} \tag{II.47}$$

Since the switch is open for a time

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \tag{II.48}$$

we can say that

$$\Delta t = (1-D)T \tag{II.49}$$

$$(\Delta i_L)_{\text{open}} = \left(\frac{V_o}{L}\right)(1-D)T \tag{II.50}$$

It is already established that the net change of the inductor current over any one complete cycle is zero.

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0 \tag{II.51}$$

$$\left(\frac{V_o}{L}\right)(1-D)T + \left(\frac{V_{\text{in}}}{L}\right)DT = 0 \tag{II.52}$$

$$\frac{V_o}{V_{\text{in}}} = \frac{-D}{1-D} \tag{II.53}$$

We know that D varies between 0 and 1. If D > 0.5, the output voltage is larger than the input; and if D < 0.5, the output is smaller than the input. But if D = 0.5 the output voltage is equal to the input voltage[8].

II.5. Comparison of Converter Types:

Table (II.1) summarizes the voltage gains and switch stresses for the different converter types. For these converters, the evolution of the voltage gains as a function of the duty cycle is shown. While several types can be considered as boost converters, particularly if the duty cycle is greater than 0.5, only the boost type provides a boosting capability over the entire duty cycle range. For a duty cycle of 0.5 for example, the boost converter exhibits an output voltage twice the input voltage. Whereas for the other boost-derived type, the output voltage is equal to the input voltage for this duty cycle value. It is only when the duty cycle approaches 1 that the other boost-derived types tend to resemble the behavior of the conventional boost type.[9].

Table (II.1): Comparison of Converter Types

Converter /Parameters	Voltage Gain $\frac{Vout}{Vin}$	Voltage Controls $V_{k,max}= \lvert Vd, max \rvert$	Current Controls $i_{k,max} = V_{d,max} = i_{d,max}$
Boost	$\frac{1}{1-\alpha}$	$\frac{Vin}{1-\alpha} + \frac{\Delta Vout}{2}$	$\frac{Iout}{1-\alpha} + \frac{\Delta IL}{2}$
Buck	$\frac{\alpha}{1-\alpha}$	$\frac{Vin}{1-\alpha} + \frac{\Delta Vout}{2}$	$\frac{VC}{1-\alpha} + \frac{\Delta Vout}{2}$
Buck-Boost	α	Vin	$i_L + \frac{\Delta IL}{2}$

II.6. Efficiency of Static Converters:

The table provides insight into the efficiency of some well-known converter types.[10]

Table (II.2): Efficiency of Static Converters.

Structure	**Conversion Efficiency**	**Battery**
Boost	92%	24V
Buck	93%	12V
Buck-Boost	92%	12-24V

II.7. Conclusion:

In conclusion, DC-DC converters are essential components in contemporary electronics, facilitating efficient power management through the conversion of one voltage level to another. With various configurations, including buck, boost, and buck-boost, these converters provide flexibility in accommodating the diverse voltage requirements of electronic systems. They are widely utilized across multiple industries, including automotive, renewable energy, telecommunications, and consumer electronics. From powering small electronic devices to regulating energy flow in solar power systems, DC-DC converters remain indispensable.

Furthermore, Maximum Power Point Tracking (MPPT) is a critical technology, particularly within renewable energy applications such as solar power systems. MPPT optimizes the extraction of maximum power from photovoltaic panels by dynamically adjusting the electrical operating point. The subsequent chapter will explore MPPT in greater detail, examining its significance and the various methods employed for its implementation.

Chapter III

Maximum Power

PointTracking

III.1. Introduction:

To address the performance limitations of solar panels and achieve maximum efficiency, it is essential to optimize the design of all components within the photovoltaic (PV) system. Furthermore, optimizing the DC-DC converters, which serve as the interface between the PV generator and the load, is crucial for continuously extracting maximum power. This optimization enables the PV system to operate at its maximum power point (MPP) without energy loss through the implementation of a Maximum Power Point Tracking (MPPT) controller. As a result, maximum power can be obtained under varying load and environmental conditions, such as changes in solar irradiance and temperature.

Since the 1970s, a substantial number of MPPT control techniques have been developed, ranging from basic methods—such as those based on voltage and current feedback—to more advanced algorithms capable of accurately calculating the PV system's MPP. Among the most widely adopted techniques are the Incremental Conductance (INC) method, the Perturb and Observe (P&O) method, and the hill-climbing method[11].

III.2. Maximum Power Point Tracking:

Improving the efficiency of photovoltaic (PV) systems requires maximizing the power output of the PV generator. This can be accomplished by appropriately selecting the operating point, thereby matching the load impedance to the voltage source. The DC-DC converter functions as an impedance adapter, ensuring operation at the optimal point and facilitating the maximum power extraction from the PV generator.[12]**.**

Maximizing the power output of a photovoltaic (PV) source requires identifying and maintaining operation at the optimal operating point, a process known as Maximum Power Point Tracking (MPPT). MPPT methods rely on iterative search algorithms to determine the operating point of the solar module that yields the maximum power output without disrupting system operation. These methods are based on the continuous optimization of the power generated by the PV modules. The power extracted from the module is calculated by measuring the current and voltage and multiplying these two quantities. Various MPPT techniques utilize these measurements to track the actual maximum power point (MPP). Several types of MPPT control methods exist, including the constant voltage method, the constant current method, the incremental conductance algorithm, and the perturbation and observation (P&O) method. In this work, the P&O method is employed due to its simplicity and ease of implementation.

III.3. Working principle of MPPT:

Specific control laws are designed to ensure that devices operate at the maximum points of their characteristics without prior knowledge of these points, the timing of their changes, or the causes of such variations. In the context of energy sources, this corresponds to the identification of maximum power points. This form of control is commonly referred to in the literature as "Maximum Power Point Tracking" (MPPT). The fundamental principle of MPPT is to continuously search for the maximum power point (MPP) while ensuring optimal matching between the generator and its load to facilitate the transfer of maximum power[13].

To simplify the operating conditions of this control, a direct current (DC) load is selected. As observed in this system, the MPPT control is necessarily associated with a four-terminal network possessing degrees of freedom that enable adaptation between the photovoltaic (PV) generator and the load. In the context of solar energy conversion, this four-terminal network can be implemented using a DC-DC converter. This configuration ensures that the power supplied by the PV generator corresponds to the maximum power (P_{MAX}) it can produce and allows the direct transfer of this power to the load..

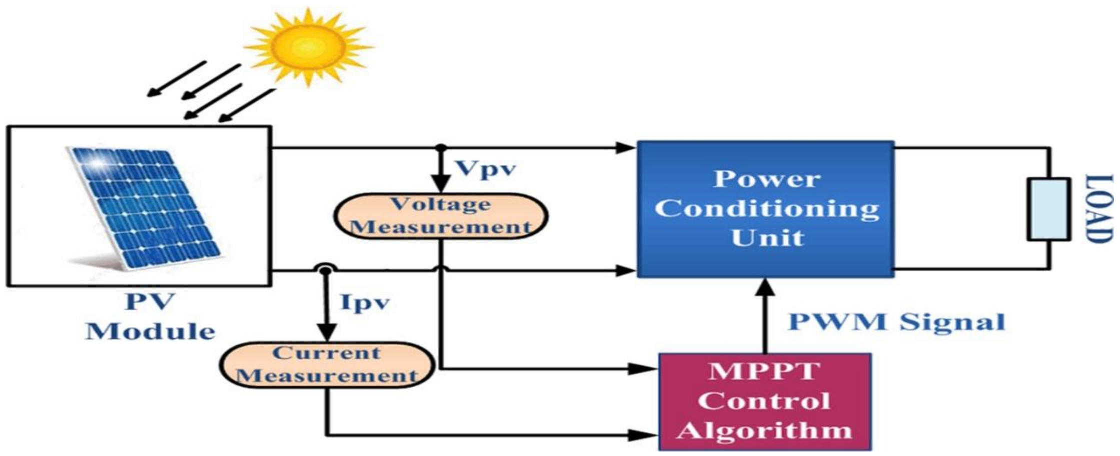

Figure (III.1): Block Diagram of The PV System

A commonly employed control technique involves automatically adjusting the duty cycle to maintain the generator at its optimal operating point, particularly in response to sudden load variations that may occur at any time. Figure (III.2) illustrates three types of disturbances. Depending on the nature of the disturbance, the operating point shifts from the initial maximum power point (MPP1) to a new operating point (P1), which may be located closer to or farther from the optimal point. In the case of solar irradiance variation (case a), it is necessary to modify the duty cycle to converge to the new maximum power point (MPP2). For load variations (case b), the operating point changes, but the system can identify and track a new optimal position through the action of the control mechanism. To a lesser extent, the operating point may also shift due to variations in the photovoltaic module's operating temperature (case c). Although adjustments must still be made at the control level in this case, the time constraints are less stringent compared to the previous two scenarios[14].

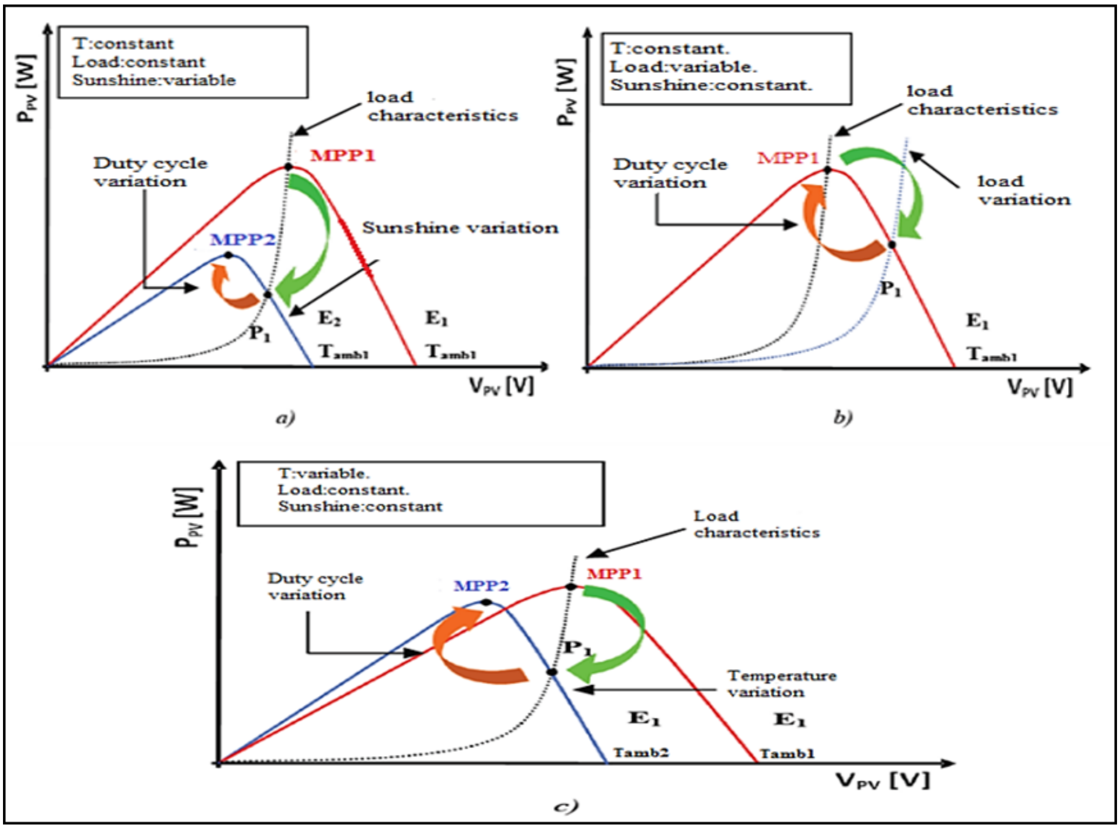

Figure (III.2): Search and Recovery Of MPP

III.4. Classification of MPPT Control:

MPPT controllers can generally be classified based on their electronic implementation into three categories: analog, digital, or hybrid. However, a more insightful classification is based on the type of search algorithm they employ and the input parameters utilized by the MPPT controller.

III.4.1. Classification of MPPT Controllers Based on Input Parameters:

a) MPPT Controllers Operating from Input Parameters:

Several MPPT controllers perform the maximum power point search by monitoring the evolution of the power generated by the photovoltaic (PV) array. Examples include the Perturb and Observe (P&O) method and incremental conductance algorithms, both of which utilize the power output of the PV array to implement appropriate control actions for tracking the maximum power point (MPP). Additionally, some controllers rely on proportional relationships between the optimal parameters that define the MPP (V_{opt} and I_{opt}) and the characteristic parameters of the PV module (V_{oc} and I_{sc}).

Notably, MPPT controllers based on neural network models also fall into this category. These controllers either rely on large computational memory systems that store all possible operating scenarios or use approximation techniques to estimate the MPP. All of these controllers offer advantages in terms of accuracy and rapid response time[15].

b) MPPT Controllers Operating from Output Parameters of the Converter:

The literature also describes algorithms based on the output parameters of DC-DC converters. For instance, MPPT controllers that maximize the output current are commonly used when the load is a battery. In all systems utilizing output parameters, the maximum power (Pmax) is estimated by considering the efficiency of the converter. In essence, the more efficient the conversion stage, the more accurate this approximation becomes. However, single-sensor systems are inherently imprecise due to their reliance on limited measurement data. Notably, many of these systems were initially developed for space applications [15].

III.4.2. Classification of MPPT Controllers According to the Type of Search:

a) Indirect MPPT:

This type of MPPT control relies on the relationship between measurable variables (such as VocV_{oc}Voc), which can be easily determined, and the approximate position of the maximum power point (MPP). It also includes control methods based on estimating the operating point of the photovoltaic (PV) system using a predefined parametric model. Additionally, some controls achieve optimal voltage tracking by accounting solely for variations in cell temperature measured by a sensor. These control methods are advantageous due to their simplicity of implementation and are primarily designed for low-cost and less precise systems operating in regions with minimal climatic variation[16].

b) Direct MPPT:

This type of MPPT control identifies the optimal operating point (MPP) based on the currents, voltages, or power measurements within the system, allowing it to respond effectively to unpredictable changes in the photovoltaic (PV) system's operation. These methods typically rely on a search algorithm to locate the MPP without interrupting system functionality. This process involves incrementing the operating point voltage at regular intervals. If the output power increases, the search direction is maintained for the next step; otherwise, the direction is reversed. As a result, the actual operating point oscillates around the MPP.

This fundamental principle is maintained across various algorithms to mitigate interpretation errors, which may arise, for instance, from an incorrect search direction due to a rapid increase in power caused by sudden changes in irradiance. Accurately determining the PV generator's power—critical for locating the MPP—requires measuring the generator's voltage and current and calculating their product. Some algorithms adopt an alternative approach by introducing small-signal sinusoidal variations in the converter's switching frequency. This method allows comparison of the alternating and direct components of the PV system's voltage, thereby positioning the operating point as close as possible to the MPP. The primary advantages of this type of control are its accuracy and rapid response time[16].

III.5. Different MPPT Commands Synthesis:

Since 1968, when the first control law adapted to renewable energy (specifically photovoltaic systems) was published, numerous studies on MPPT control techniques have appeared regularly in the literature. Due to the extensive number of publications in this field, MPPT methods can be classified according to their underlying principles.

III.5.1. First MPPT Commands Types:

The algorithm implemented in the first MPPT control system was relatively simple. This simplicity was primarily due to the limited processing capacity of microcontrollers available at that time and the reduced environmental constraints, particularly in space applications, regarding temperature and solar irradiation. The first MPPT control applied to a photovoltaic system was introduced by A.F. Boehringer. This control method was based on an adaptive control algorithm designed to maintain the system at its maximum power point (MPP). As illustrated in Figure 3, the algorithm can be easily implemented on a computer. The system calculates the power at time tit_iti using the measured values of IPVI_{PV}IPV and VPVV_{PV}VPV, and compares it to the previously stored power value from time ti−1t_{i-1}ti−1. Based on this comparison, a new duty cycle DDDis computed and applied to the static converter[16].

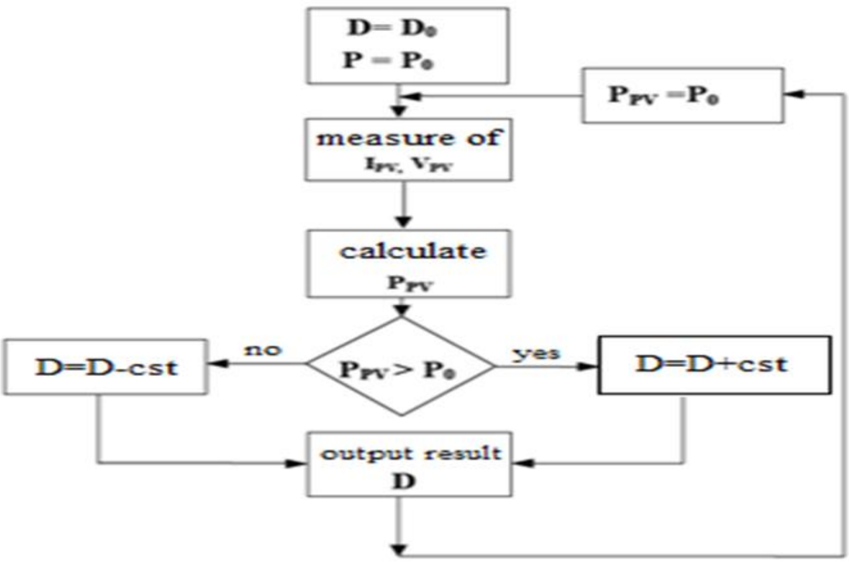

Figure (III.3): Bloc Diagram of a Digital MPPT Command

This principle remains theoretically valid and is still applied in modern, more efficient numerical algorithms. However, advancements have led to improvements in both the response time and the accuracy of the maximum power point (MPP) tracking process[14].

III.5.2. Efficient MPPT Commands Algorithms:

The four methods most commonly encountered in Maximum Power Point Tracking (MPPT) are commonly referred to as Hill Climbing, Perturb and Observe (P&O), Incremental Conductance, and Fuzzy Logic controllers.

III.5.2.1. Algorithm Perturb and Observe (P&O):

The principle of MPPT control methods based on the Perturb and Observe (P&O) technique involves perturbing the photovoltaic voltage (VPVV_{PV}VPV) with a small amplitude around its initial value and analyzing the resulting variation in power (PPVP_{PV}PPV). As illustrated in Figure (III.4), if a positive increment in VPVV_{PV}VPV leads to an increase in PPVP_{PV}PPV, it indicates that the operating point is located to the left of the maximum power point (MPP). Conversely, if the power decreases, it suggests that the system has surpassed the MPP.

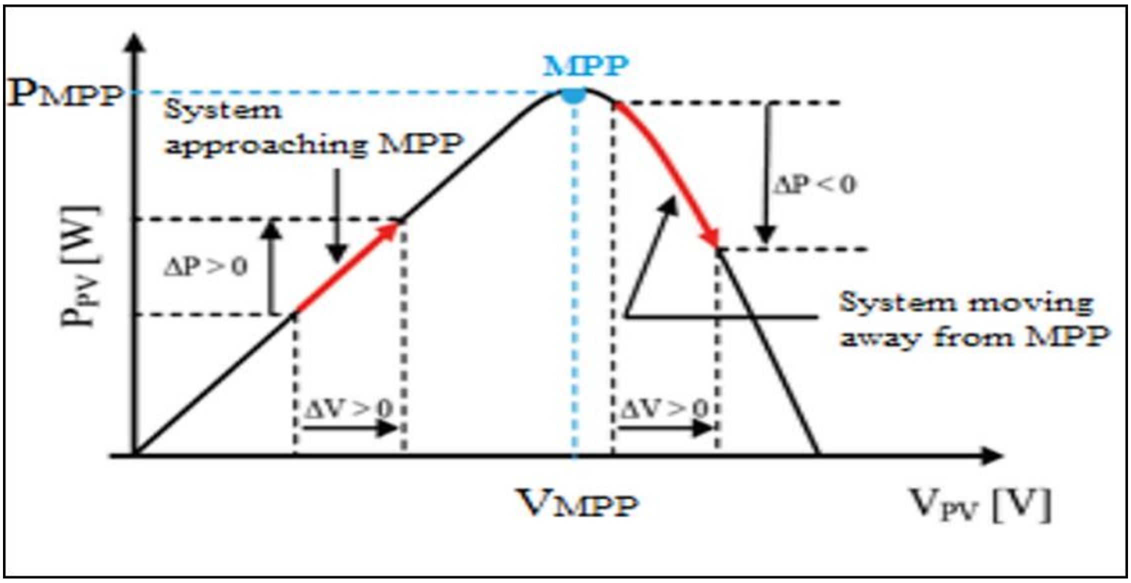

Figure (III.4): Ppv VS Vpv Characteristic of a Solar Panel

Figure (III.5) shows the algorithm associated with a conventional MPPT command of the P & O type, where the evolution of the power is analyzed after each voltage disturbance. For this type of command, two sensors (current and voltage) are needed to determine the power of the solar generator at every instant of time. The Perturb & Observe method is nowadays widely used because of its ease of implementation.

However, it has some problems associated with oscillations around the MPP it generates in steady state because the search of the MPP should be repeated periodically, causing the system to oscillate continuously around the MPP.

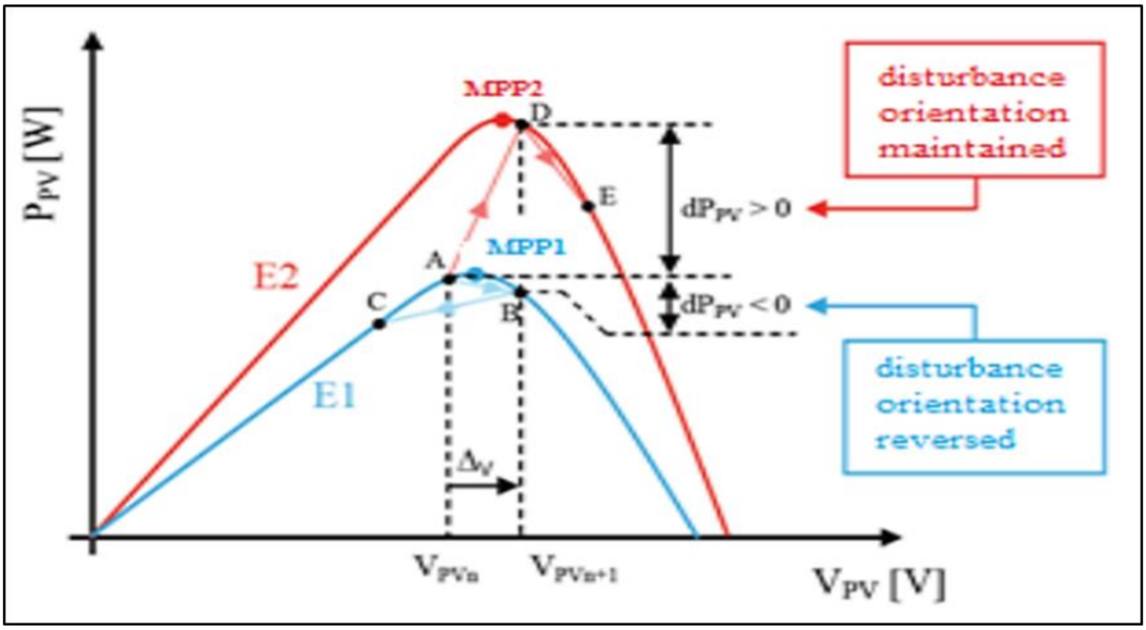

Figure (III.5): Divergence of The P & O Command Due to Radiation Variations

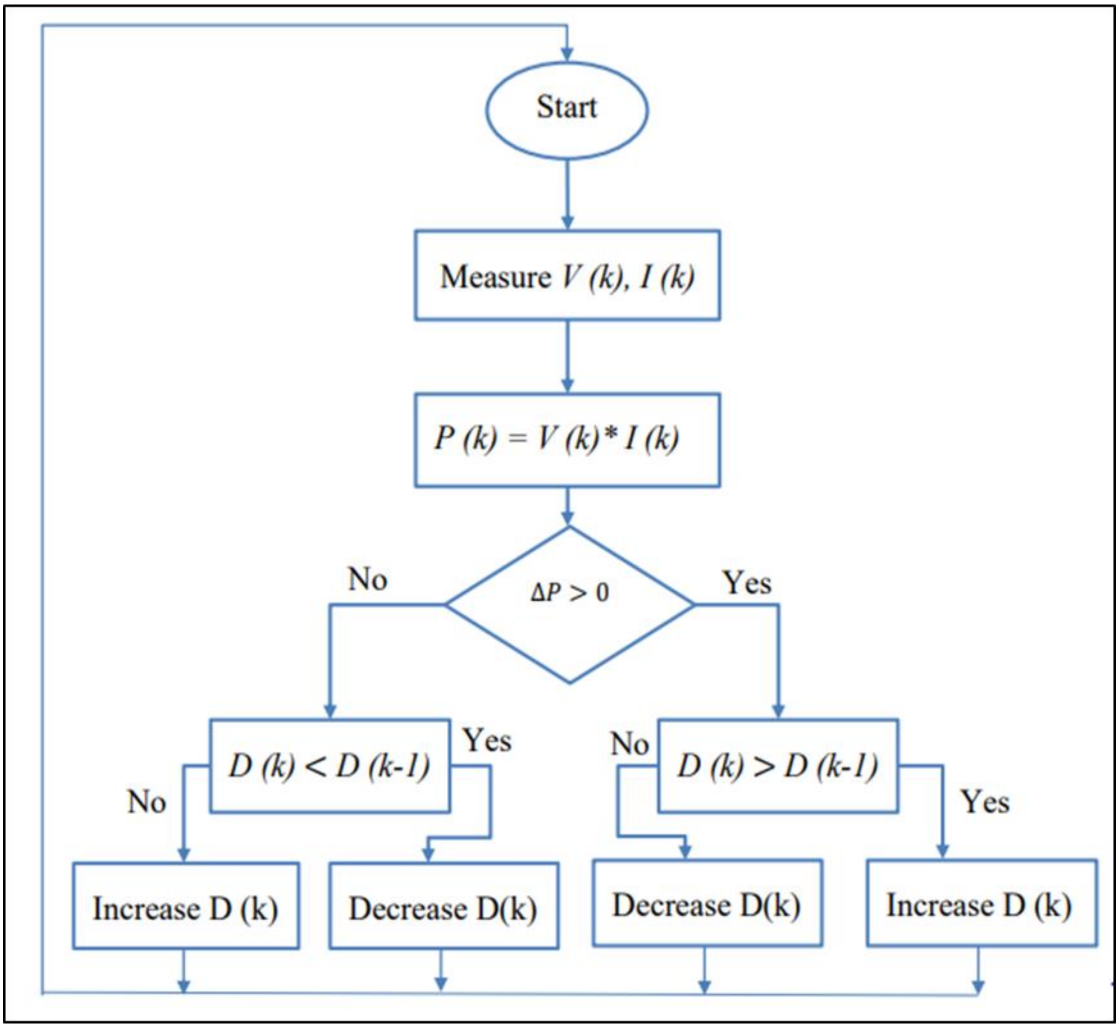

Figure (III.6): Algorithm of The P & O Type of Command

To understand this, consider the example of a given solar irradiation, E1, with an operating point lying in A. following a voltage disturbance of value ΔV, it switches to B, implying a variation of operating without illumination, a reversal of the sign of the disturbance due to the detection of a negative sign for the derivative of the power resulting, in equilibrium, in oscillations around the MPP due to the path of the operating point between points B and C. it can be noted that losses of power transfer will be more or less important depending on the respective positions of points B and C with respect to A. When changing the irradiation of the module from E1 to E2, the operating point then moves from A to D, which is interpreted in this case as a positive power variation[14].

III.5.2.2. Algorithm Hill Climbing:

The best thing about the hill climbing MPPT method is its simplicity. It uses the duty cycle of the boost converter as feedback parameter when the task of the MPPT is carried out[17],[18]. The main disadvantage of this technique is due to the trade-off between the stability of the system in a period of constant irradiation. Another disadvantage is the absence of a rapid response in case of a rapid change in radiation[17],[18]. The period of steady radiation requires a very small value of variation in the duty cycle, ΔD to avoid a strong oscillation of the power about the peak power point, reducing the energy captured by the PV. On the other hand, rapidly changing irradiation requires a higher duty cycle value to accelerate the pursuit of peak power.

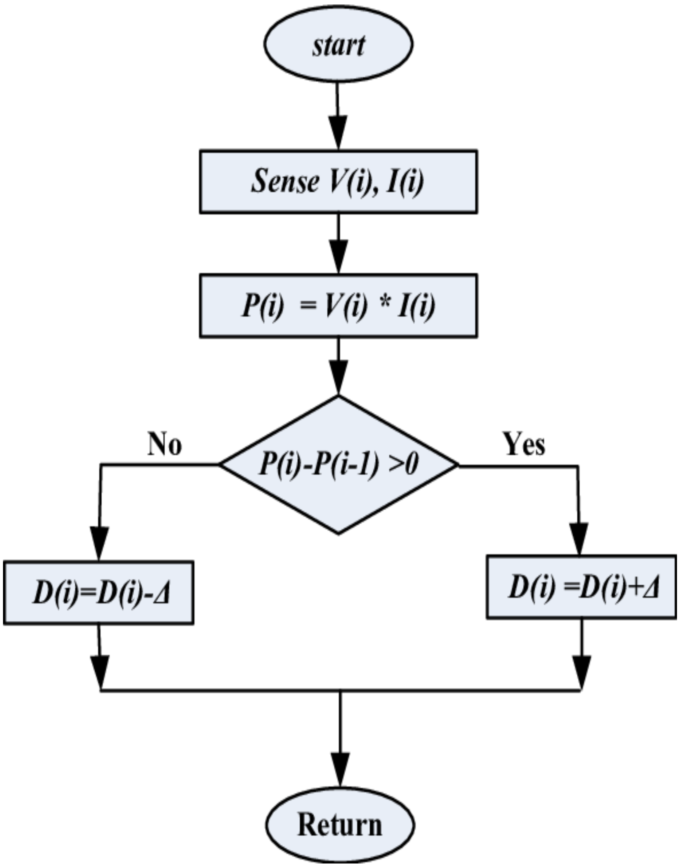

Figure (III.7): State Flowchart of Hill Climbing MPPT Technique.

III.5.2.3. Algorithm Incremental conductance (INC):

The principle of this algorithm is based on knowledge of the conductance value G=I/V and the conductance increment (dG) in order to deduce the position of the operating point relative to the maximum power point. If the conductance increment (dG) is greater than the negative of the conductance (-G), the duty cycle is decreased. On the other hand, if the conductance increment is less than the negative of the conductance, the duty cycle is increased. This process is repeated until the maximum power point is reached[19].

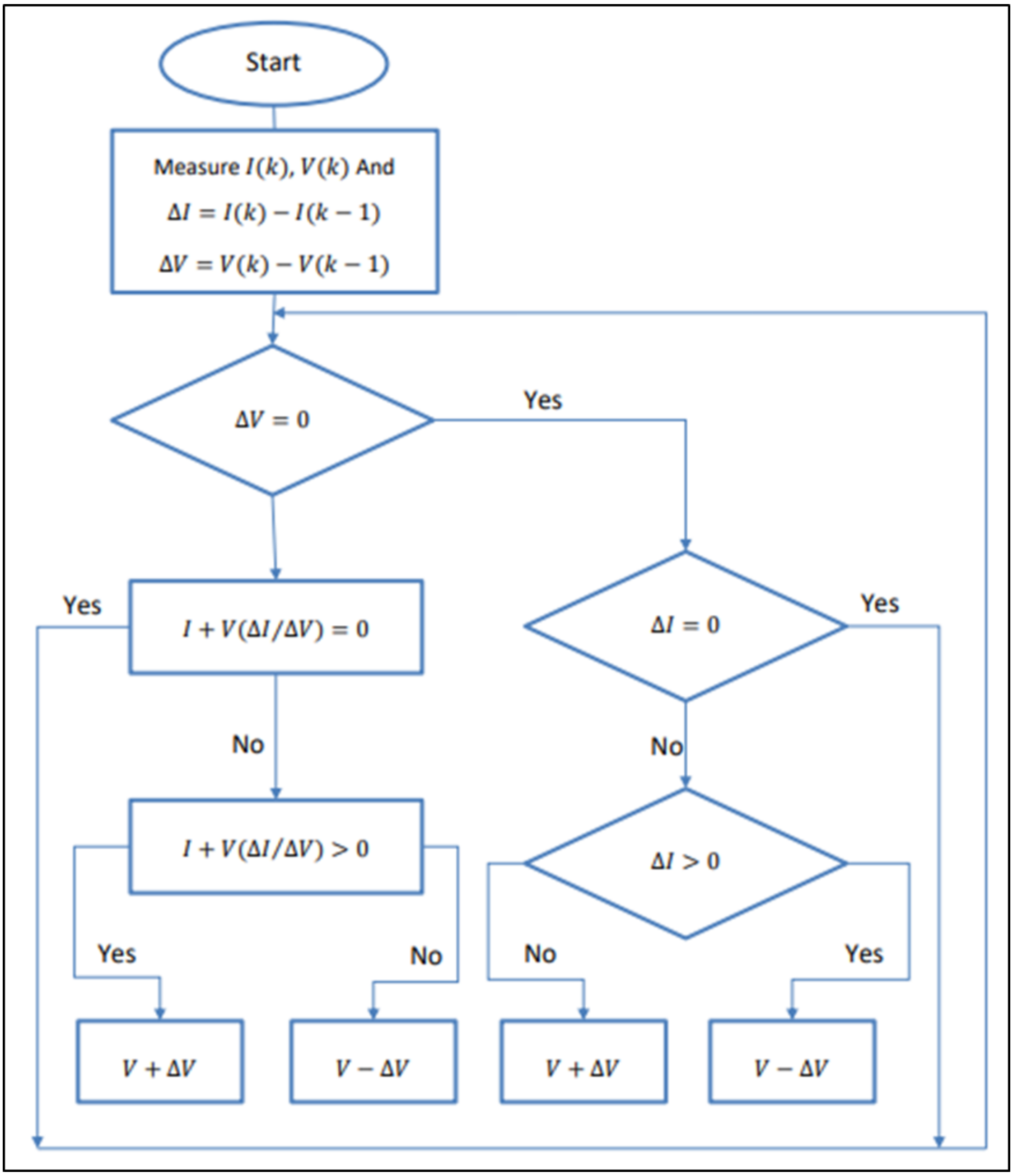

Figure (III.8): Flowchart for The Incremental Conductance Algorithm.

III.5.2.4. The MPPT based Fuzzy Logic Controller:

Renewable energy resources have a wide range of applications for Fuzzy Logic Controllers (FLCs). Over the past decade, the demand for FLCs has increased due to their simplicity.

FLCs also handle imprecise input and do not require an accurate mathematical model for the controller.

They can easily manage nonlinear conditions to extract maximum power from PV modules.

Moreover, FLCs are capable of operating under any weather condition or changes in temperature or irradiance levels. [8].

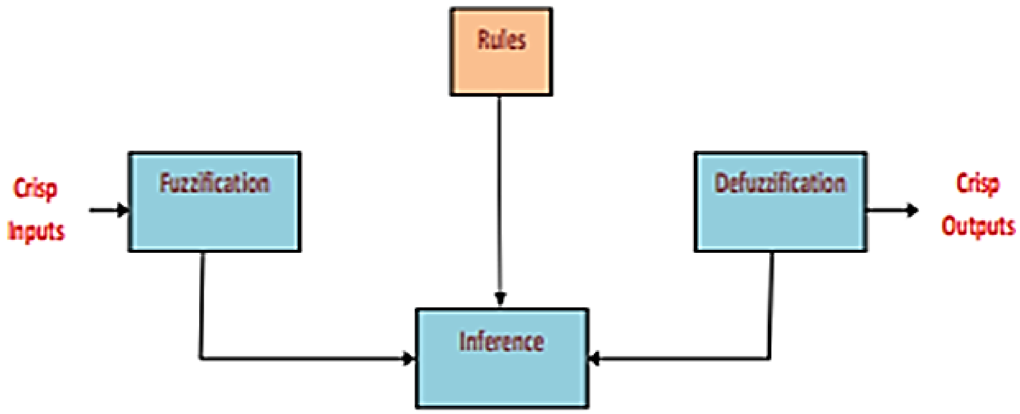

Figure (III.9): The Stages of Fuzzy Logic Controller

The fuzzy logic controller process can be assorted into three categories:

- Fuzzification
- Rule Evaluation
- Defuzzification

The first category, i.e., Fuzzification, takes the crisp input, for example, the change in input voltage levels.

After taking the crisp input, it converts it into fuzzy input using the stored membership functions.

Once the fuzzy values are designed, the first stage of the FLC — fuzzification — is completed.

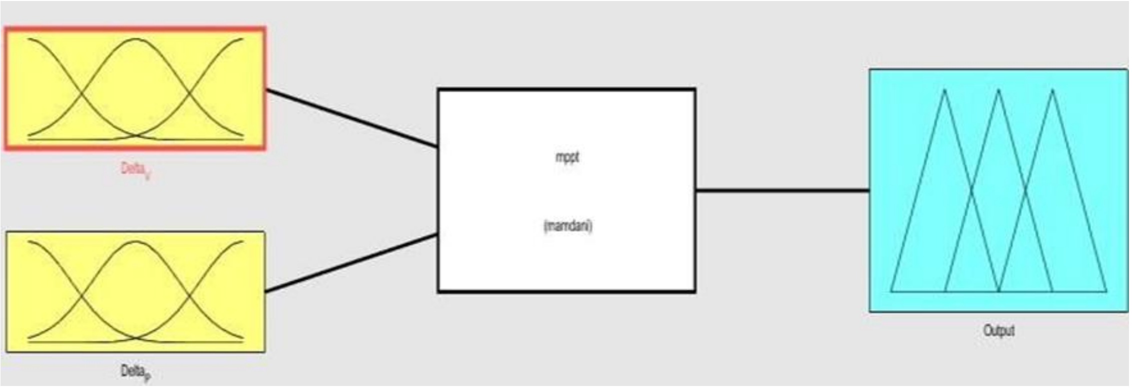

Figure (III.10): The FLC

The second category of the fuzzy logic controller is Rule Evaluation.

This stage involves a fuzzy processor that uses linguistic rules to determine the control action in response to a set of input values.

The rule evaluation process always produces fuzzy outputs as the result of each action.

The final category in the fuzzy logic controller process is the Defuzzification technique.

In this stage, the fuzzy value is converted into a crisp value. The expected output is always a crisp value derived from the fuzzy set.

In the FLC process, every fuzzy output variable is effectively transformed with respect to the output membership function corresponding to each input set.

The Center of Gravity (COG) is the most commonly used defuzzification technique; it is also known as the centroid method [8,10].

In this project, the fuzzy logic controller is used in the MPPT controller, which is connected to the Perturb and Observe (P&O) algorithm.

The integration of FLC into MPPT improves the output voltage, and designing a fuzzy logic controller is relatively simple.

It does not require deep knowledge of the exact system model; it only requires assigning rules to each set of the membership function [8–13].

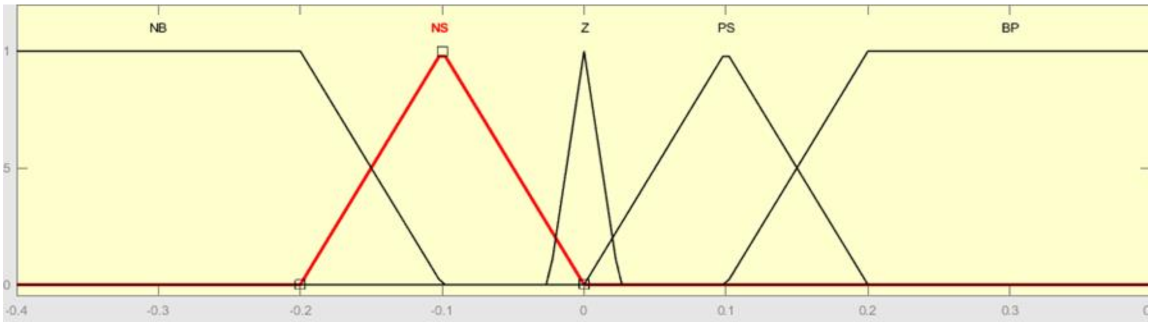

Figure (III.11).embership function of input Variable Delta_P

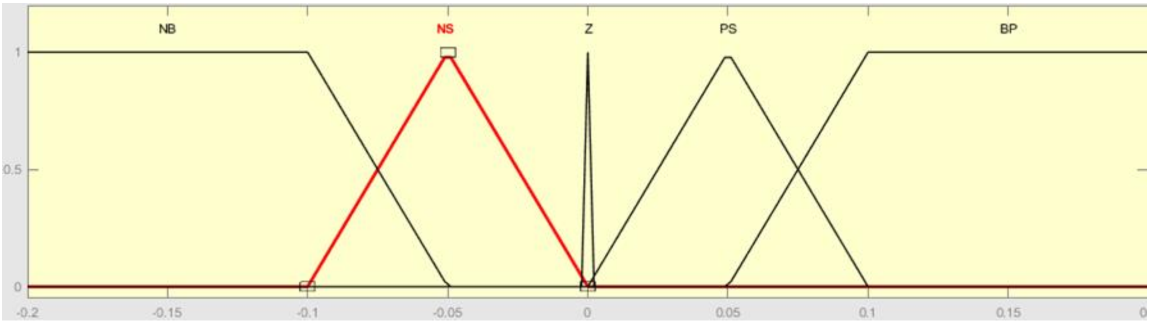

Figure (III.12) Membership function of input Variable Delta_V

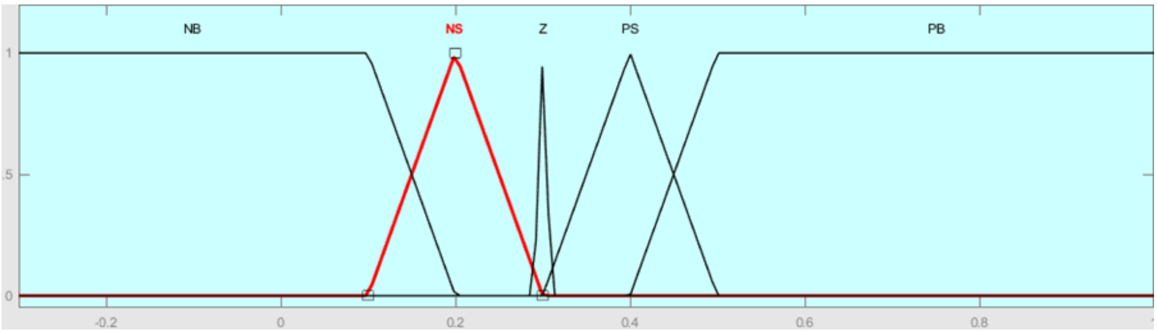

Figure (III.13) Membership Function of Output Variable Delta_Y

In this paper, a new method is introduced that utilizes a Fuzzy Logic Controller (FLC) for designing a Maximum Power Point Tracking (MPPT) system for PV modules under uncertain environmental conditions.

By applying this method, the oscillations around the Maximum Power Point (MPP) are significantly reduced.

This method performs better compared to the conventional Perturb and Observe (P&O) algorithm.

There are two input variables provided to the fuzzy logic controller:

- ΔV (Delta_V): the change in voltage of the PV module
- ΔP (Delta_P): the change in power of the PV module

The output from the fuzzy logic controlleris ΔY (Delta_Y).

This output is then fed to a sampling signal, which processes it and sends it to the boost converter to generate appropriate switching pulses. [14].

III.5.2.5. 1. Rule Evaluation

The rule base designed for the MPPT block within the FLC divides the input and output variables intolinguistic levels:

- NB – NegativeBig
- NS – Negative Small
- ZE – Zero
- PS – Positive Small
- PB – Positive Big

These variables are applied in relation to the sampling time.

During the fuzzification process, the numerical inputs are converted into linguistic variables based on predefined membership functions.

The design of MPPT rules is based on the idea that a change in voltage that increases power should be continued in the same direction.

If the power decreases, the direction of change should be reversed in the next step.

After the theoretical design, membership functions and rules were adjusted through trial and error to achieve maximum performance. [15–17].

Table (III.1): Rule-Basedused in FLC

ΔV \ ΔP	NB	NS	Z	PS	PB
NB	PB	PS	NB	NS	NS
NS	PS	PS	NB	NS	NS
Z	NS	NS	NS	PB	PB
PS	NS	PB	PS	NB	PB
PB	NB	NB	PB	PS	PB

III.6. Conclusion :

In this chapter, we have begun the most important and most delicate part of this study. This involves presenting the principle of searching for the maximum power point while giving the different classifications of MPPT commands. We have detailed the different MPPT methods encountered most often in literature. The existence of several types of MPPT commands shows that this area of research is constantly evolving and that it is difficult to find one or more universal solutions.

Chapter IV

SimulationResults

IV.1. Introduction:

In this chapter, we delve into the performance evaluation and comparison of three widely recognized Maximum Power Point Tracking (MPPT) algorithms Perturb and Observe (P&O), Incremental Conductance (INC), and Fuzzy Logic controllers. These algorithms play a crucial role in optimizing the power output of photovoltaic (PV) systems by continuously adjusting the operating point to ensure maximum energy extraction from solar panels. By accurately tracking the maximum power point, these algorithms help in maximizing the efficiency and effectiveness of PV systems, which is essential for improving the overall performance and energy yield. The P&O algorithm relies on periodic perturbations and observations to find the optimal point, whereas the INC algorithm uses the incremental conductance method for finer adjustments. The ANN algorithm, on the other hand, leverages artificial intelligence to predict and track the maximum power point with high precision. Our comprehensive analysis aims to highlight the strengths and weaknesses of each algorithm, providing valuable insights into their suitability for different operating conditions.

IV.2. Parameters of System Simulation:

The following characteristics of panel and the parameters of boost converter that are used in our system simulation, are shown in the figure and table below:

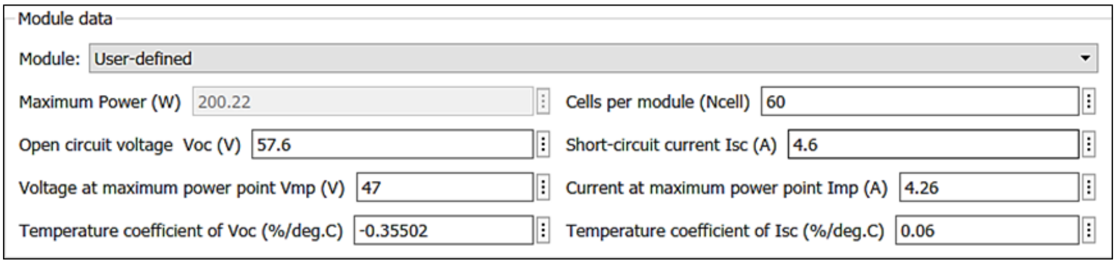

Figure (IV.1): Characteristics of Panel

Table (IV.1): Parameters of Boost Converter

Boost Converter	Value
Capacitor 1	200 µF
Inductor	3.5 mH
Capacitor 2	100 µF
Resistive Load	300 Ω

IV.3. Simulation Results:

IV.3.1. P&O Algorithm:

In this simulation, we used the Perturb and Observe (P&O) algorithm to obtain results for power, voltage, and current. Figure (IV.2) represents the general system simulation, showcasing the overall setup and performance of the P&O -based MPPT system. The figure illustrates the integration of PV panels with the P&O -based MPPT controller, which adjusts the duty cycle to optimize power extraction.

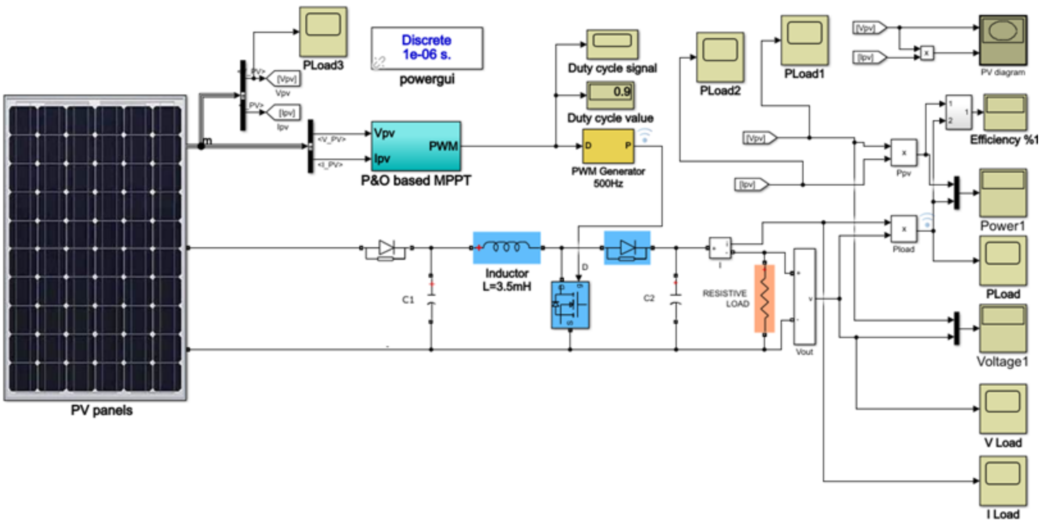

Figure (IV.2): SchemaofSystem SimulationWith P&O

a) Constant Irradiance (1000 W/m^2) :

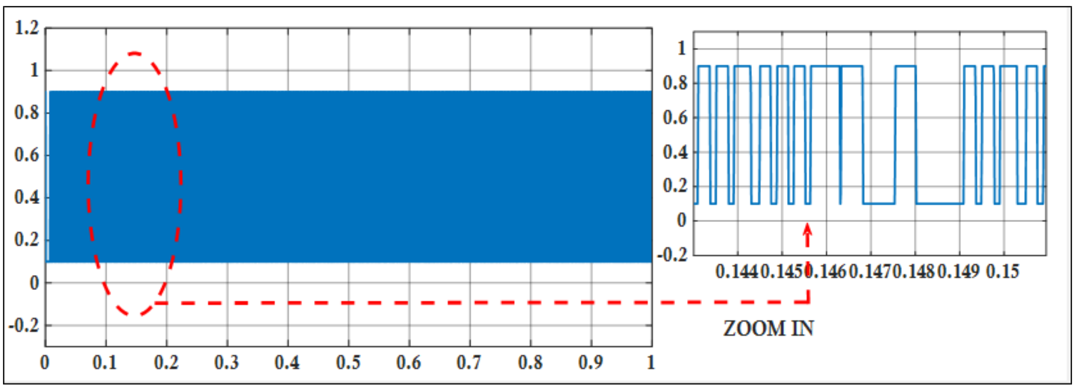

Figure (IV.3): Duty Cycle Simulation Result

The Figure (IV.3) demonstrates the MPPT system's duty cycle behavior, with the main plot showing overall stability and the zoomed-in view revealing critical fluctuations for precise MPPT operation.

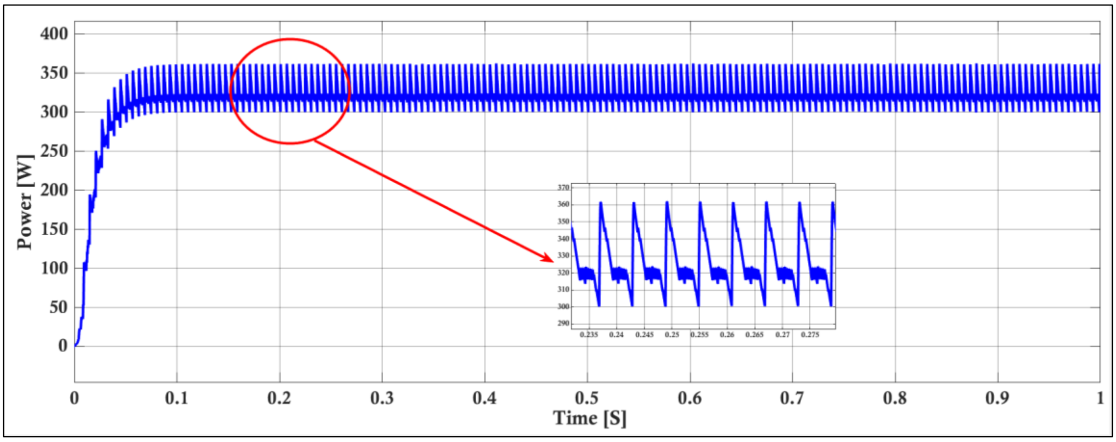

Figure (IV.4): Power Simulation Result

The Figure(IV.4) illustrates the power response of an MPPT system using the P&O algorithm. The main plot shows a rapid increase in power followed by stabilization around 350W. The zoomed-in view highlights the oscillatory nature of the power output, characteristic of the P&O algorithm as it continuously perturbs to track the maximum power point. These oscillations are a trade-off for maintaining optimal power extraction and are crucial for understanding the efficiency and performance of the MPPT system.

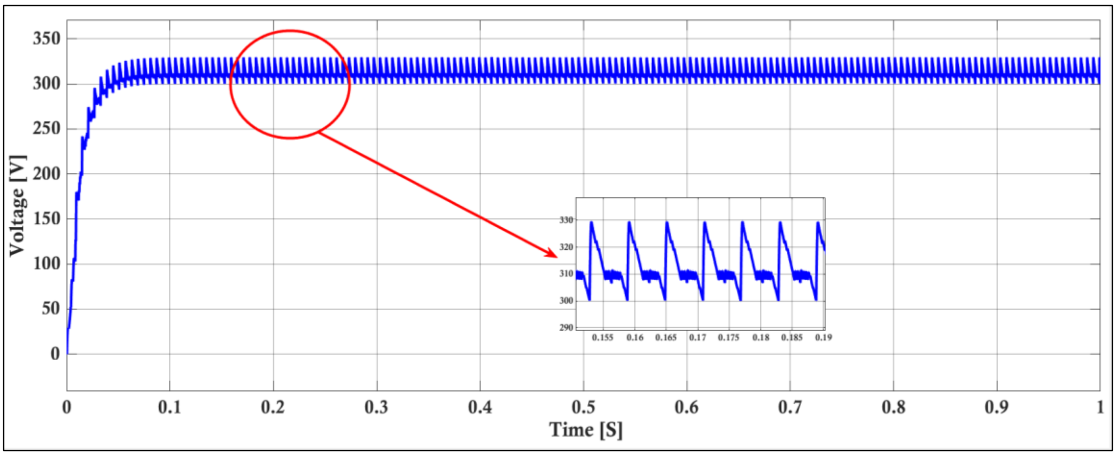

Figure (IV.5): Voltage Simulation Result

The Figure (IV.5)illustrates the voltage response of an MPPT system using the P&O algorithm. The main plot shows a rapid increase in voltage, stabilizing around 320V. The zoomed-in view highlights the oscillatory nature of the voltage output.

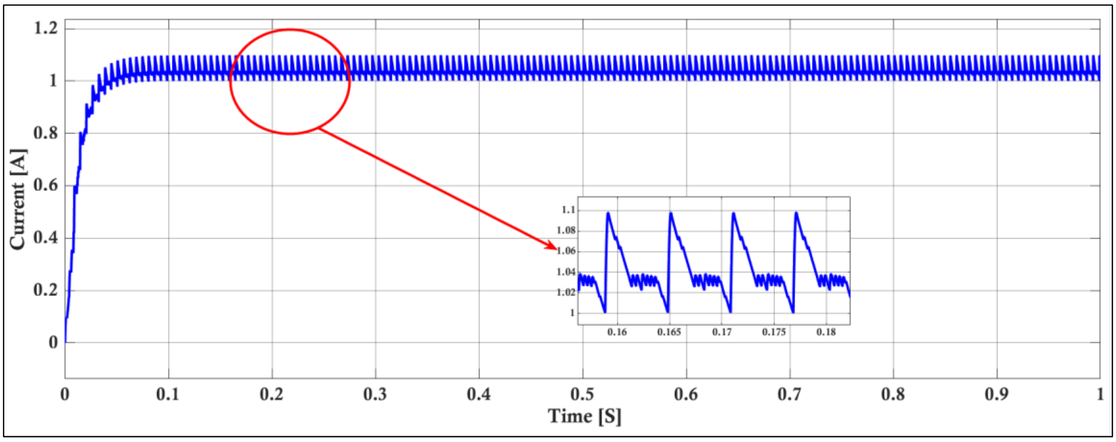

Figure (IV.6): Current Simulation Result

The Figure (IV.6)illustrates the current response of an MPPT system using the P&O algorithm. the main plot shows the rapid transient response leading to stabilization at approximately 1.05A, indicative of the system reaching its maximum power point. The zoomed-in view provides a closer look at the inherent oscillations around this steady-state value

b) Variable Irradiances (1000,600, 400 W/m^2) :

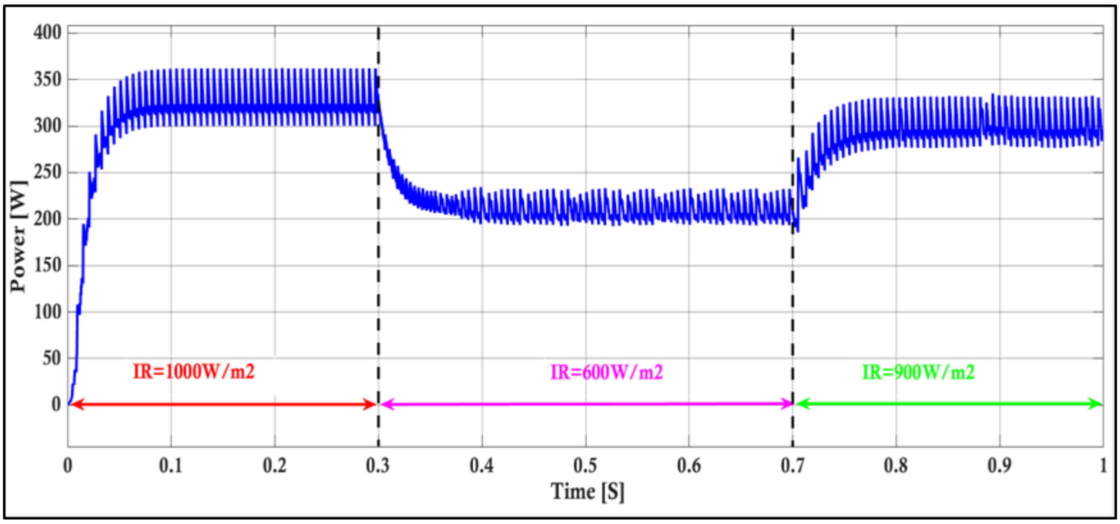

Figure (IV.7): Power Simulation Result

The Figure (IV.7) provides a comprehensive view of the MPPT system's power output behavior under varying irradiance levels. The main plot demonstrates the system's ability to track the maximum power point across different irradiances, with power stabilizing at approximately 350 W, 300W, 250W, and 200W for IR levels of 1000 W/m², 800 W/m², 600 W/m², and 400 W/m², respectively. The red dashed ellipse and zoomed-in view emphasize the system's transient response to a sudden drop in irradiance, showcasing the characteristic oscillations as the P&O algorithm adjusts to the new maximum power point. This detailed analysis underscores the efficiency and adaptability of the MPPT system in real-time solar energy applications

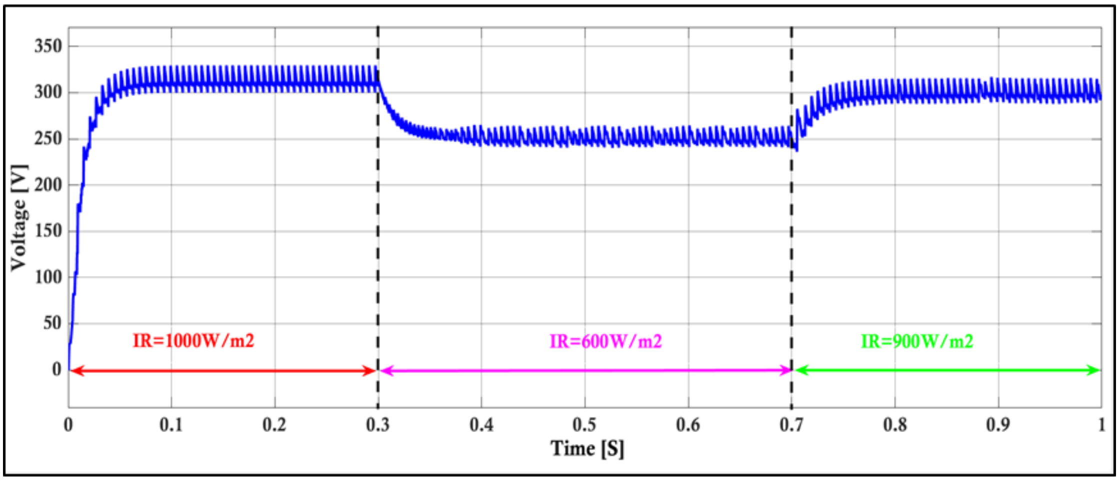

Figure (IV.8): Voltage Simulation Result

The Figure (IV.8)demonstrates how the voltage of an MPPT system using the P&O algorithm adjusts to varying irradiance levels. The main plot shows the system's quick voltage stabilization at around 320V, followed by stepwise decreases as the irradiance drops. The zoomed-in view provides a detailed look at the transient fluctuations, illustrating the algorithm's continuous adjustments to maintain optimal performance.

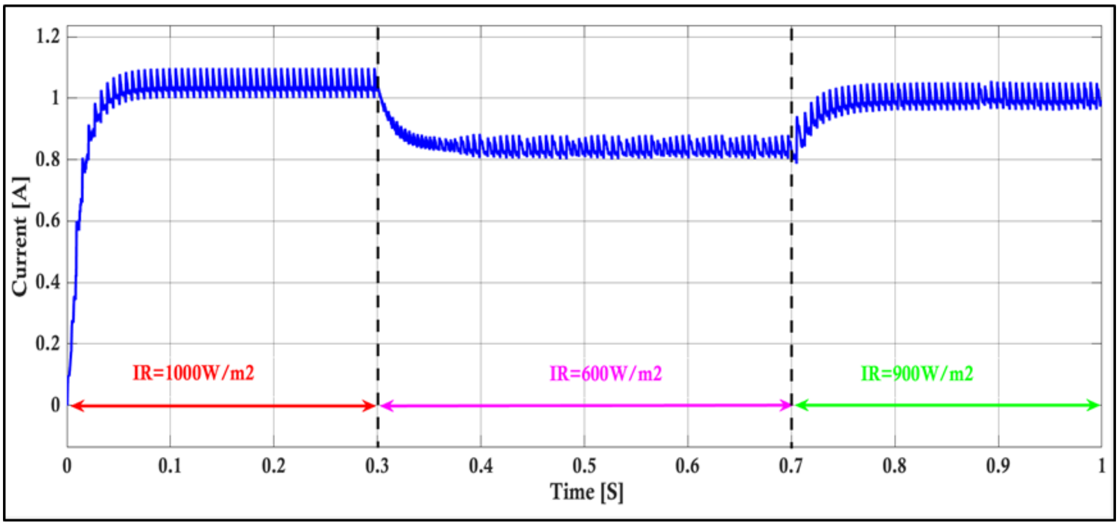

Figure (IV.9): Current Simulation Result

The Figure (IV.9)demonstrates how the MPPT system's current output, managed by the P&O algorithm, adjusts under varying irradiance levels. The main plot shows the current stabilizing around 1A and decreasing in steps as irradiance diminishes. The zoomed-in view captures the transient response during an irradiance change.

IV.3.2. Incremental Conductance:

In this simulation, we used the Incremental Conductance (INC) algorithm to obtain results for power, voltage, and current. Figure (IV.10)represents the general system simulation, showcasing the overall setup and performance of the INC-based MPPT system. The figure illustrates the integration of PV panels with the INC-based MPPT controller, which adjusts the duty cycle to optimize power extraction.

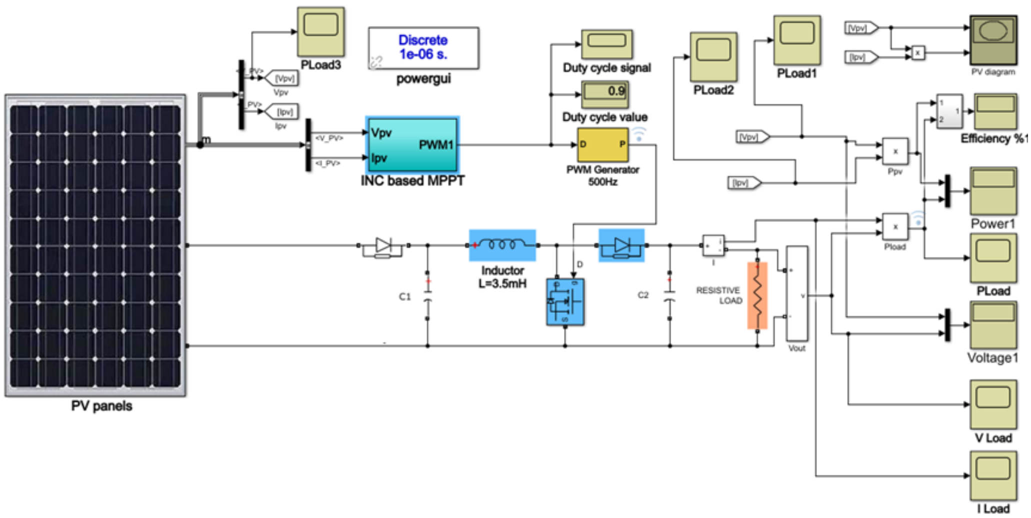

Figure (IV.10): Schema of System Simulation With INC

a) **Constant Irradiance (1000 W/m^2) :**

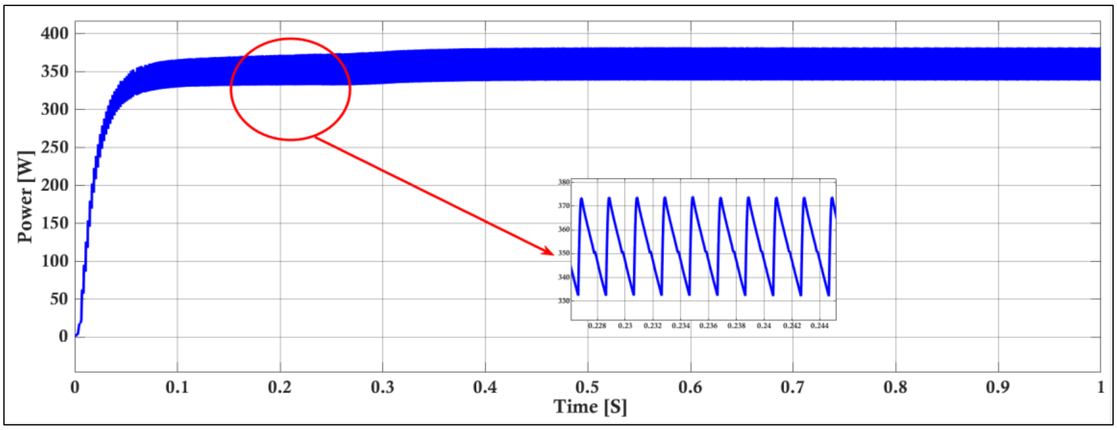

Figure (IV.11): Power Simulation Result

The Figure (IV.11)demonstrates the power stabilization behavior of an MPPT system managed by the Incremental Conductance algorithm. The main plot shows a rapid rise and stabilization of power at approximately 370W, reflecting the system's efficiency. The zoomed-in view highlights periodic fluctuations, illustrating the algorithm's continuous adjustments to maintain optimal power output. This analysis underscores the Incremental Conductance algorithm's capability to dynamically track the maximum power point with precision.

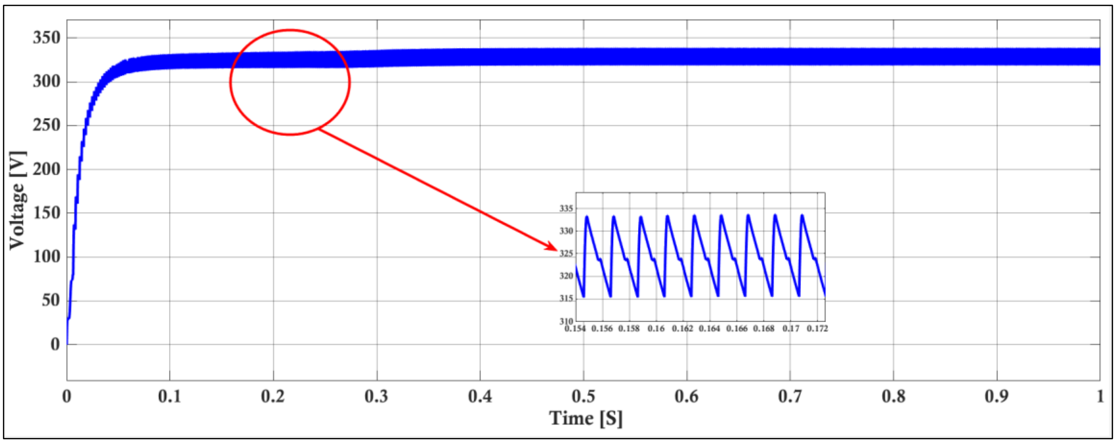

Figure (IV.12): Voltage Simulation Result

The Figure (IV.12)demonstrates the voltage response of an Incremental Conductance-based MPPT system. The main plot shows the voltage stabilizing around 330V, while the zoomed-in view captures small fluctuations.

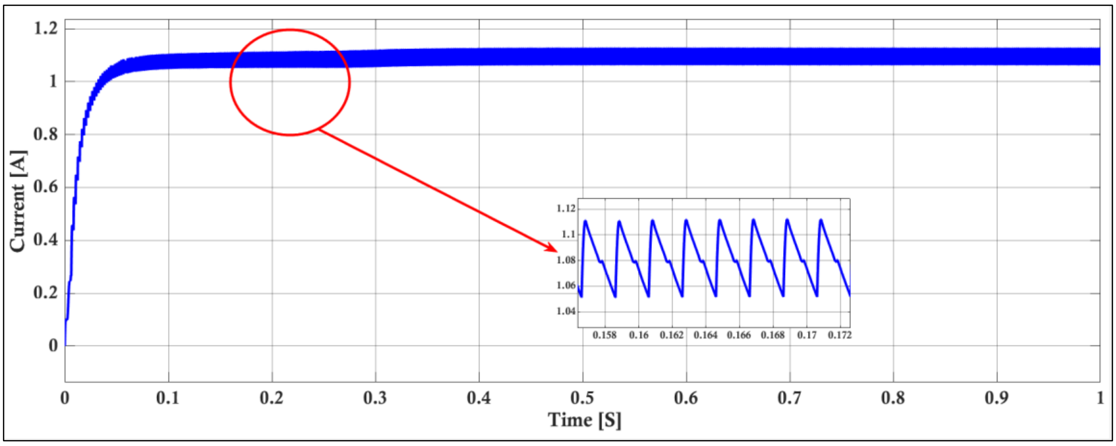

Figure (IV.13): Current Simulation Result

The Figure (IV.13)demonstrates the current stabilization behavior of an MPPT system managed by the Incremental Conductance algorithm. The main plot shows the current quickly rising and stabilizing around 1.1A, indicating the system's efficiency in reaching the maximum power point. The zoomed-in view highlights small fluctuations in the current.

b) Variable Irradiances (1000, 600, 400 W/m^2):

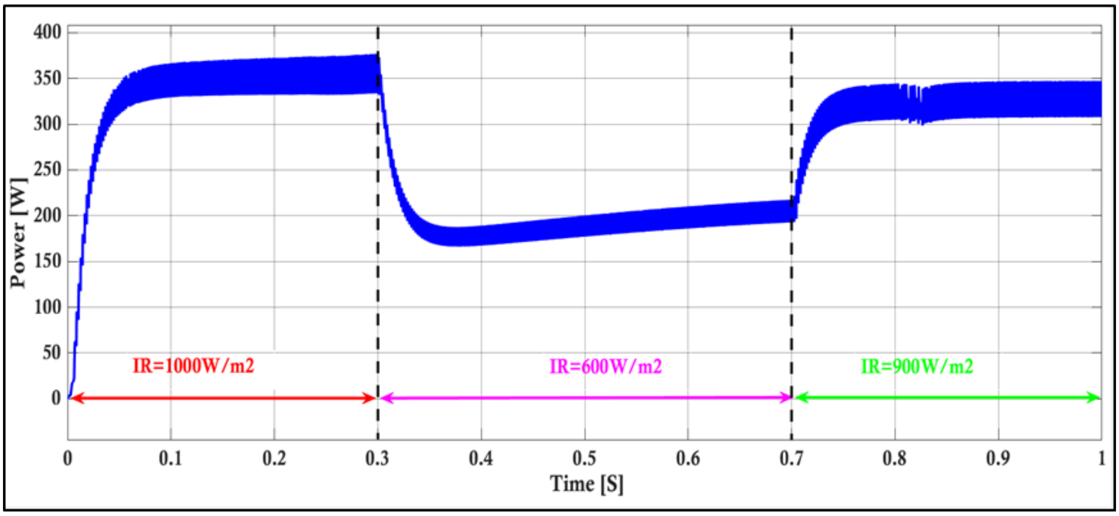

Figure (IV.14): Power Simulation Result

The Figure (IV.14)demonstrates the power response of an MPPT system using the Incremental Conductance algorithm under varying irradiance conditions. The main plot shows the power stabilizing around 350W initially, with stepwise decreases as the irradiance drops. The zoomed-in view captures the transient fluctuations during an irradiance change.

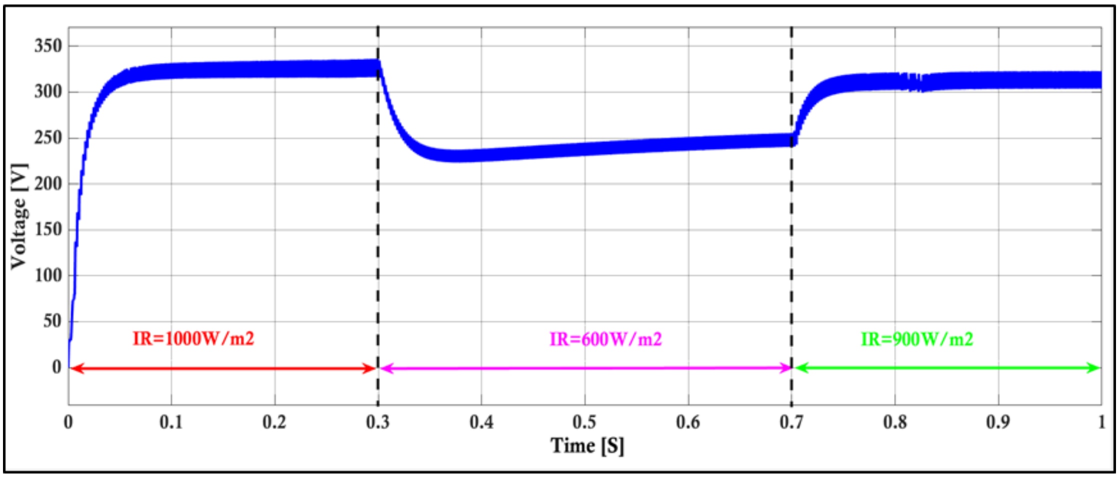

Figure (IV.15): Voltage Simulation Result

TheFigure (IV.15)demonstrates the voltage response of an Incremental Conductance-based MPPT system to varying irradiance levels. The main plot shows a rapid rise and stabilization around 330V, with stepwise decreases as irradiance drops. The zoomed-in view highlights transient fluctuations,

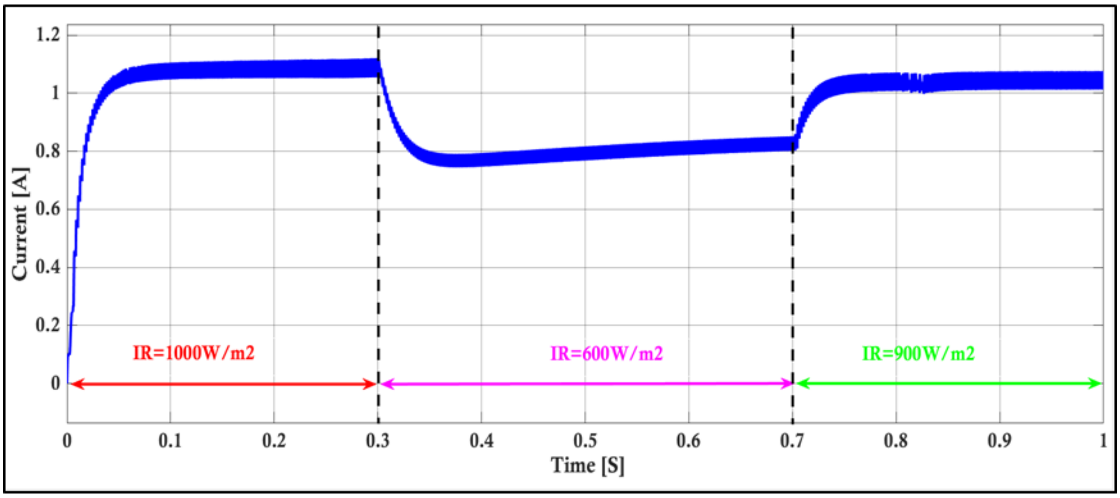

Figure (IV.16): Current Simulation Result

The Figure (IV.16)demonstrates the current response of an MPPT system using the Incremental Conductance algorithm under varying irradiance conditions. The main plot shows the current stabilizing around 1.1A initially, with stepwise decreases as the irradiance drops. The zoomed-in view captures transient fluctuations during an irradiance change.

IV.3.3. Fuzzy Logic controllers:

In this simulation, we used the Fuzzy Logic controllers algorithm to obtain results for power, voltage, and current. Figure (IV.17)represents the general system simulation, showcasing the overall setup and performance of the FLC -based MPPT system. The figure illustrates the integration of PV panels with the FLC -based MPPT controller, which adjusts the duty cycle to optimize power extraction.

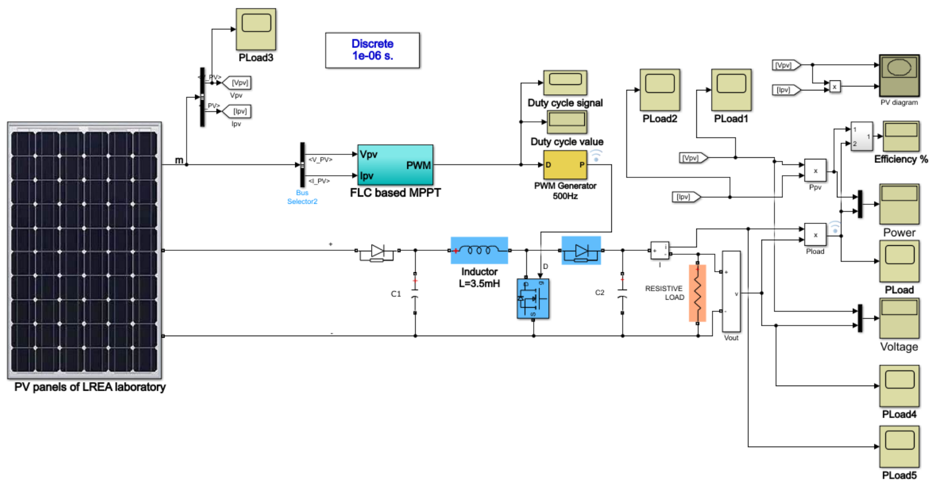

Figure (IV.17): Schema of System SimulationWith FLC

a) Constant Irradiance (1000 W/m^2) :

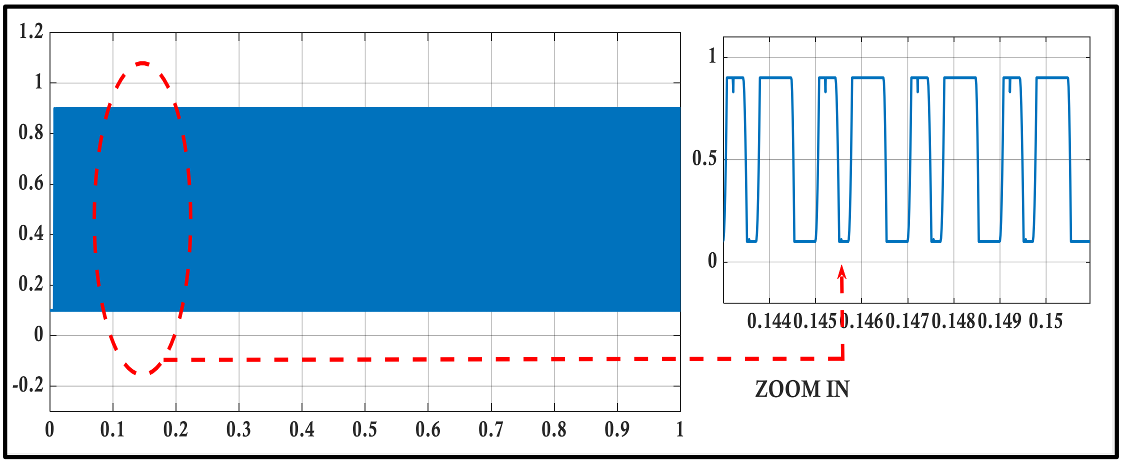

Figure (IV.18): Duty Cycle Simulation Result

The Figure (IV.18) demonstrates the stability and fine-tuning of the duty cycle by an FLC -based MPPT system. The main plot shows a stable duty cycle near 1, while the zoomed-in view reveals periodic adjustments, indicating the FLC 's responsiveness to optimize performance.

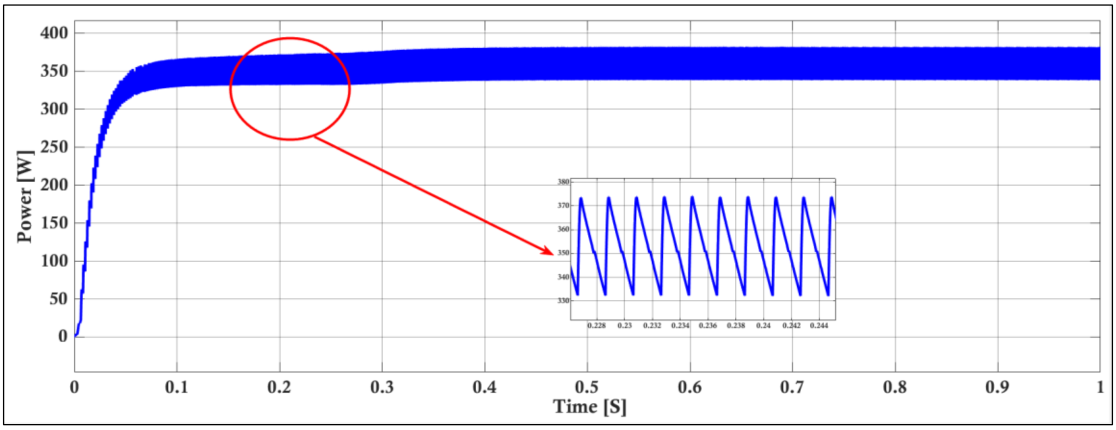

Figure (IV.19): Power Simulation Result

The Figure (IV.19) demonstrates the power stabilization behavior of an MPPT system managed by an FLC algorithm. The main plot indicates a rapid rise and stabilization of power at approximately 380W, reflecting the system's efficiency. The zoomed-in view highlights periodic fluctuations, illustrating the FLC 's ongoing adjustments to maintain optimal power output. This analysis underscores the FLC algorithm's capability to dynamically track the maximum power point with precision.

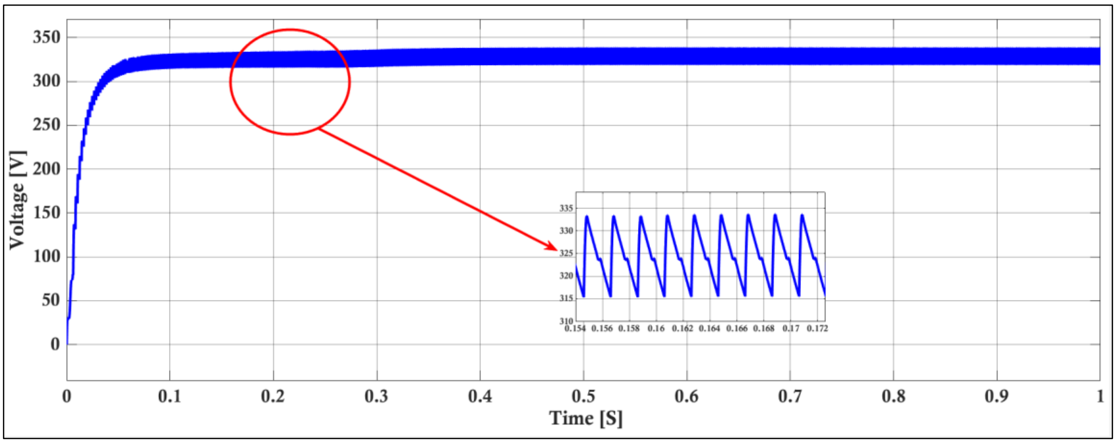

Figure (IV.20): Voltage Simulation Result

The Figure (IV.20) illustrates the voltage behavior of an FLC -based MPPT system. The main plot shows a quick rise and stabilization around 335V, while the zoomed-in view captures small fluctuations.

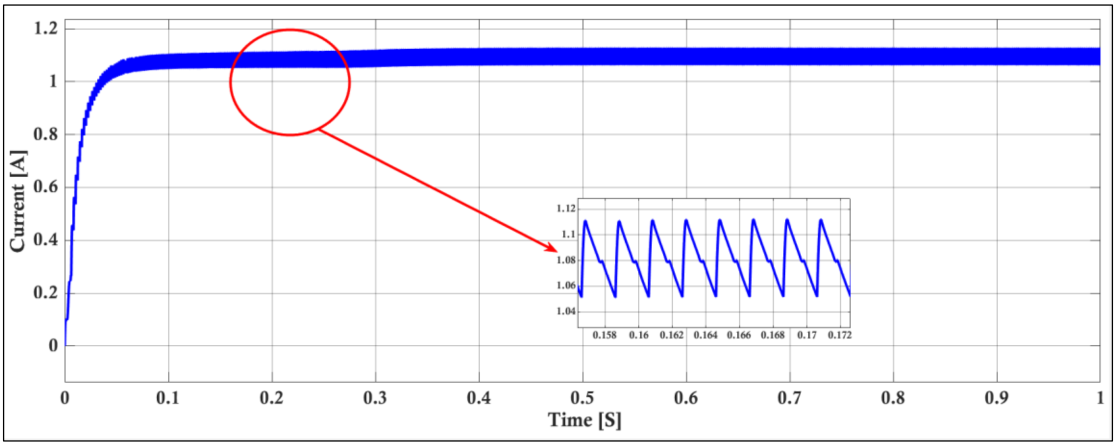

Figure (IV.21): Current Simulation Result

The Figure (IV.21) shows the current stabilization of an FLC -based MPPT system. The main plot displays a rapid rise in current, stabilizing around 1.1A. The zoomed-in view highlights small fluctuations.

b) Variable Irradiances (1000, 600, 400 W/m²):

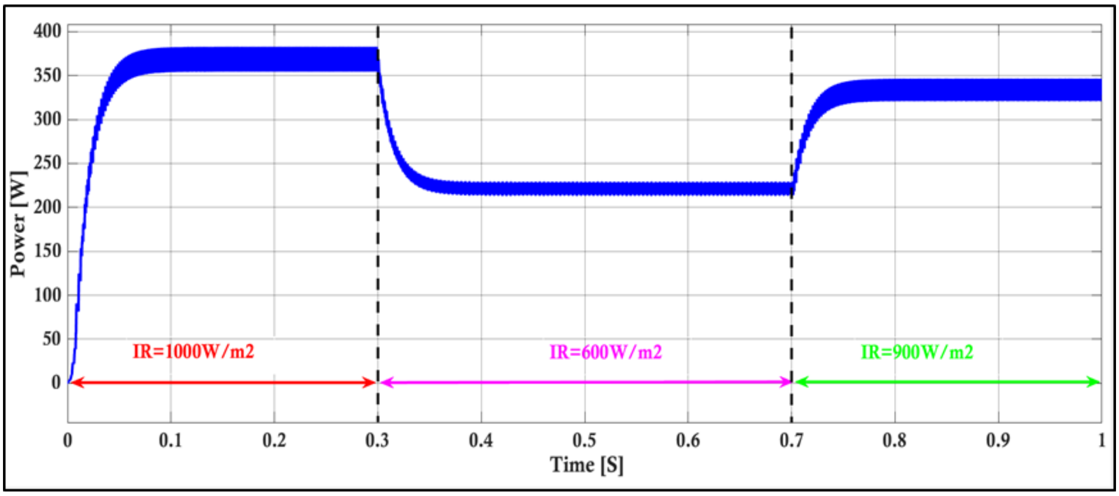

Figure (IV.22): Power Simulation Result

The Figure (IV.22) demonstrates how the FLC -based MPPT system adjusts its power output under varying irradiance conditions. The main plot shows the power stabilizing at approximately 350W initially, with stepwise decreases as the irradiance drops. The zoomed-in view captures the transient fluctuations during an irradiance change.

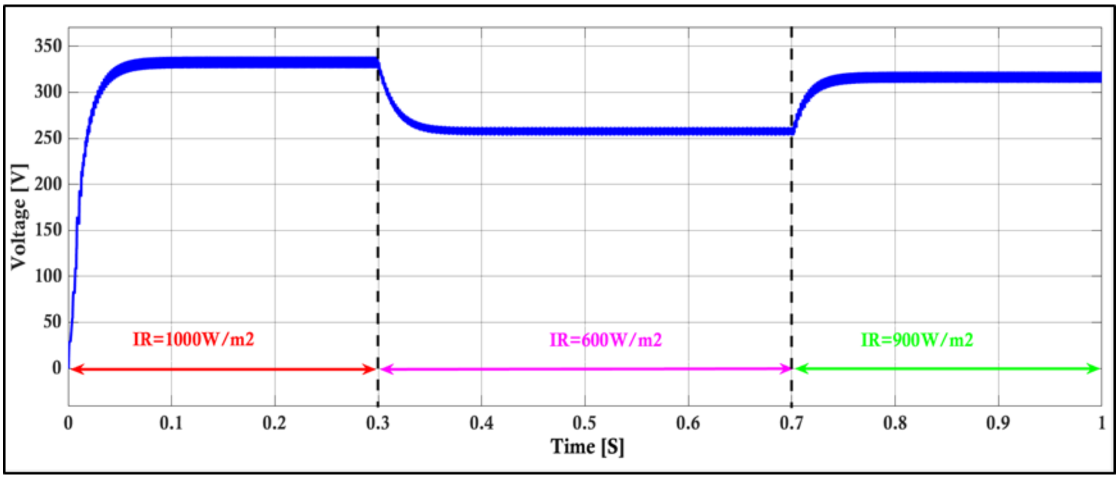

Figure (IV.23): Voltage Simulation Result

The Figure (IV.23)illustrates the FLC -based MPPT system's voltage response to varying irradiance. The main plot shows the voltage stabilizing around 330V and stepping down with decreasing irradiance. The zoomed-in view highlights transient fluctuations This demonstrates the algorithm's capability to dynamically adjust to real-time changes in solar irradiance, ensuring efficient performance.

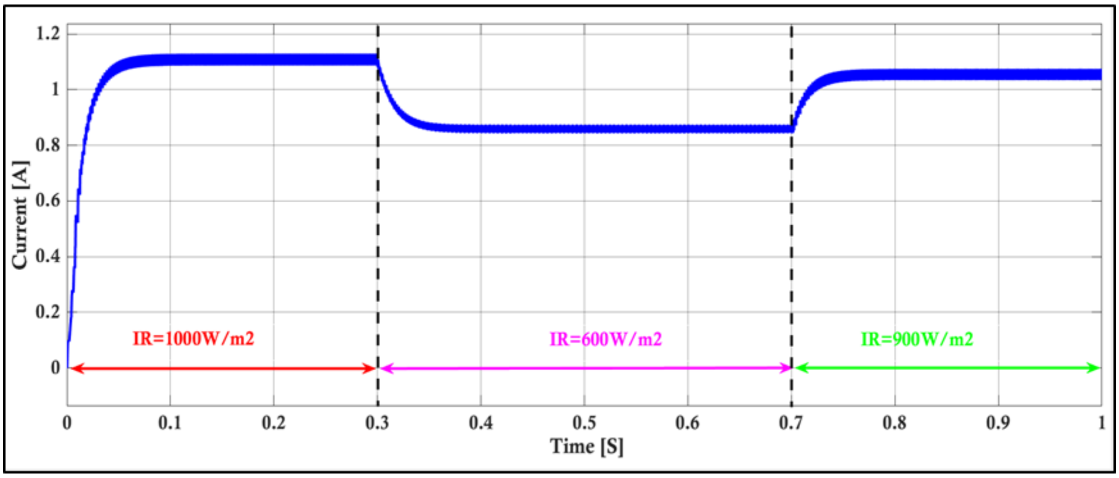

Figure (IV.24): Current Simulation Result

The Figure (IV.24) demonstrates the current response of an FLC -based MPPT system under varying irradiance conditions. The main plot shows the current stabilizing around 1.1A initially, with stepwise decreases as the irradiance drops. The zoomed-in view captures transient fluctuations during an irradiance change.

IV.4. Comparison of efficiency between algorithms (P&O, INC, FLC):

IV.4.1. Constant Irradiance(1000 W/m^2):

Table(IV.2): Table of Efficiency

Algorithm	**Efficiency**
Perturb and Observe (P&O)	95.29%
Incremental Conductance (INC)	96.15%
Fuzzy Logic controllers (FLC)	97.20%

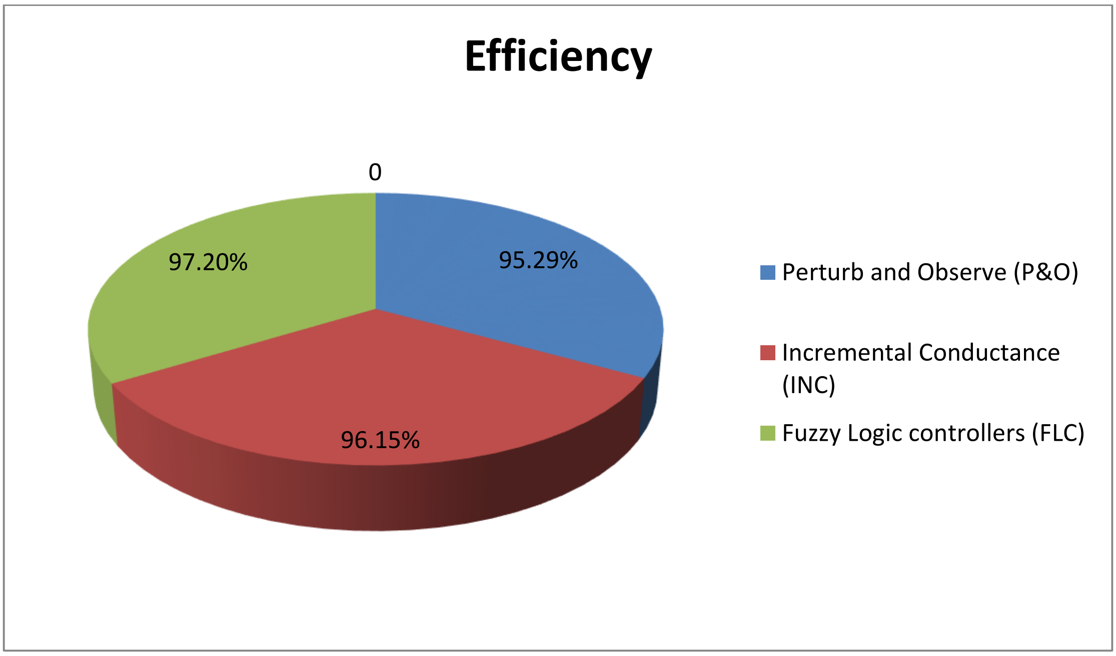

Figure (IV.29): Chart of Efficiency

Under constant irradiance of 1000 W/m², the Fuzzy Logic controllers algorithm exhibits the highest efficiency, approximately 97%. The Incremental Conductance (INC) algorithm follows with an efficiency of around 96%, while the Perturb and Observe (P&O) algorithm records the lowest efficiency at approximately 95%. These results indicate that the FLC algorithm is the most effective in optimizing power output under stable irradiance conditions, outperforming both the INC and P&O algorithms.

IV.4.2. Variable Irradiances (1000, 800, 600, 400W/m^2):

Table(IV.3): Table of Efficiency

Algorithm	**Efficiency**
Perturb and Observe (P&O)	85.41%
Incremental Conductance (INC)	88.61%
Fuzzy Logic controllers (FLC)	95.63%

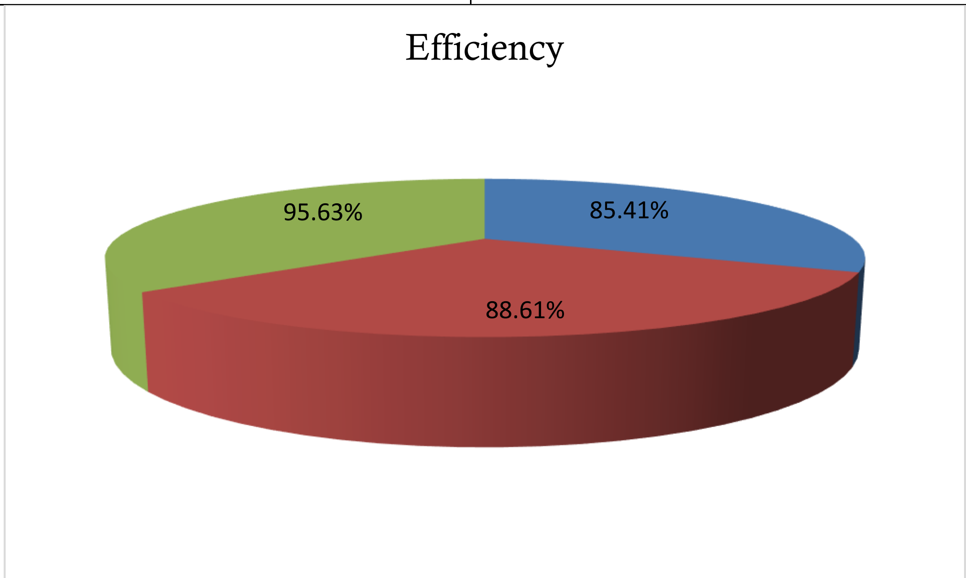

Figure (IV.30): Chart of Efficiency

Under conditions of variable irradiance, the Fuzzy Logic controllers algorithm exhibits the highest efficiency, approximately 95%, demonstrating its superior capacity to adapt to fluctuating light conditions. The Incremental Conductance (INC) algorithm follows with an efficiency of around 88%, indicating satisfactory performance, albeit with reduced stability relative to the FLC. The Perturb and Observe (P&O) algorithm records the lowest efficiency at approximately 85%, reflecting a greater vulnerability to fluctuations under varying irradiance conditions. These findings underscore the effectiveness of the FLC algorithm in optimizing power output within dynamic environments

IV.5. Conclusion:

The Fuzzy Logic controllers algorithm stands out as the most effective and reliable MPPT method in this study. Its superior efficiency, stability, and adaptability under both steady and dynamic irradiance conditions make it the best choice for optimizing photovoltaic system output. The Incremental Conductance (INC) algorithm, while performing better than P&O, still falls short of FLC's advanced capabilities. Despite its common use, the Perturb and Observe (P&O) algorithm is the least effective in this comparison, demonstrating lower efficiency and greater instability. Therefore, for maximizing energy extraction and ensuring reliable performance, the FLC algorithm is the recommended MPPT method

General Conclusion

General Conclusion

This study began by laying the foundation for understanding solar radiation and photovoltaic energy conversion principles. It explained how solar cells harness the photovoltaic effect to generate electricity from sunlight, and discussed the modeling, characteristics, and factors influencing the efficiency of photovoltaic generators. Different photovoltaic cell types based on silicon crystal structures were also presented.

Building upon this, the crucial role of DC-DC converters in power management systems was explored. These converters facilitate efficient voltage conversion through various topologies like buck, boost, and buck-boost, enabling their widespread use across diverse industries.

The concept of Maximum Power Point Tracking (MPPT) was then introduced as a vital technology, particularly for renewable energy systems such as solar power installations. MPPT algorithms optimize energy extraction by continually adjusting the electrical operating point to track the maximum power output of photovoltaic panels.

This naturally led to an in-depth examination of MPPT principles, classifications, and implementation methods. Among the various MPPT algorithms evaluated, the Fuzzy Logic controllers approach emerged as the most effective and reliable. Its superior efficiency, stability, and adaptability under both steady and dynamic irradiance conditions make it the recommended method for maximizing energy extraction and ensuring robust performance in photovoltaic systems.

While other algorithms like Incremental Conductance showed better performance than the commonly used Perturb and Observe method, they still fell short of the advanced capabilities offered by ANN-based MPPT. Consequently, for optimizing photovoltaic system output and ensuring long-term, reliable operation, the ANN algorithm stands out as the optimal solution among the methods studied.

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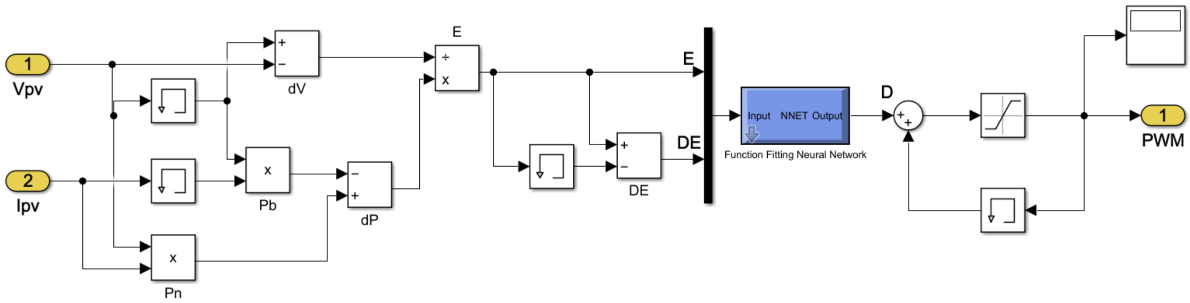
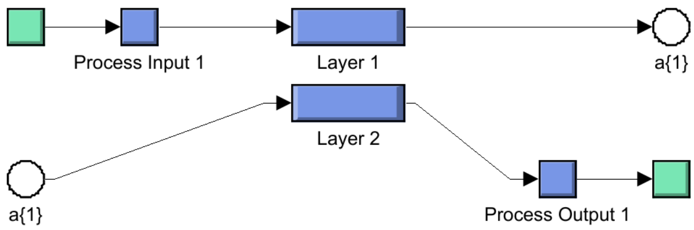
ANN





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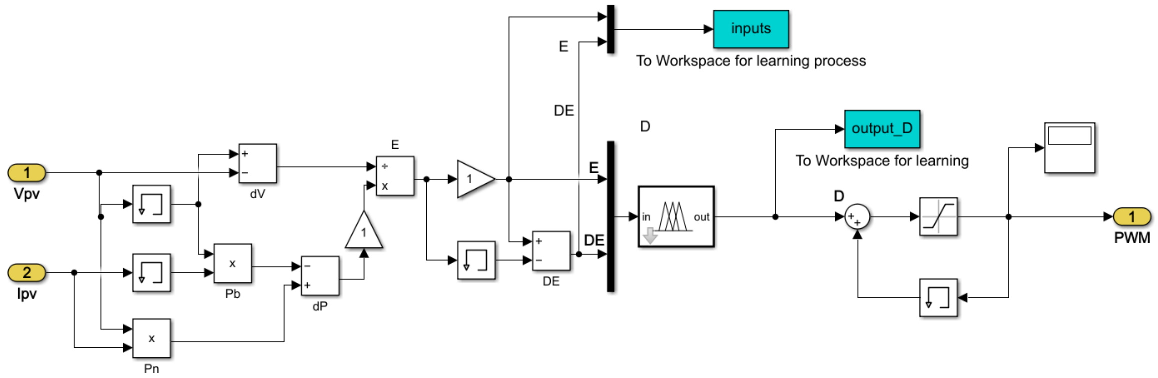
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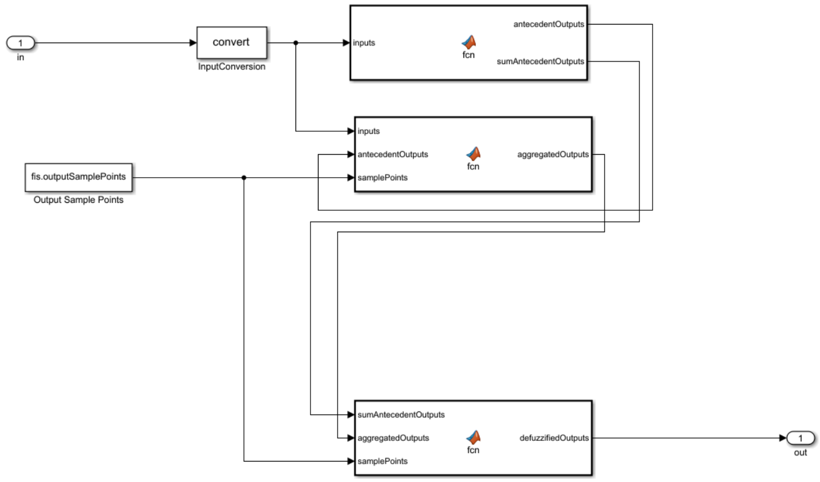
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