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TITLE

Enhancing Grid-Connected Photovoltaic System Performance Using Artificial Intelligence

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Dedication

At the beginning, I thank ***ALLAH*** *for giving me the strength and health to let this work see the light.*

I dedicate this modest work:

To my dear and beloved mother and father, who paved the path I have walked and did everything in their power to ensure my success in life. They have wished nothing but the best for me may Allah protect them.

To my kind-hearted brothers Abdel Razzak, Abdel Salam, and Amine, as well as my sister Halima, who have always supported and encouraged me throughout these years of study.

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Dedication

*First, I would like to thank **ALLAH** Almighty for granting me the patience and strength to complete this work.*

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Abdelrazak

ملخص:

تتناول هذه المذكرة استخدام المنطق الضبابي في تحسين أداء نظام كهروضوئي متصل بشبكة كهربائية. في البداية، تم وصف نظام الطاقة الكهروضوئي بما في ذلك مبدأ عمله، مكوناته الرئيسية وربطه مع الشبكة. بعد ذلك، تم استخدام خوارزمية "التشويش والمراقبة" (P&O) للبحث عن نقطة الاستطاعة العظمى (MPP)، أين تم العرف على حدودها. بالإضافة إلى ذلك، تم اقتراح خوارزمية ذكية تعتمد على المنطق الضبابي للتحكم في طاقة النظام الكهروضوئي المدروس وتسييرها في النمطين بدون تتبع أو تتبع نقطة الاستطاعة العظمى (MPP). أظهرت نتائج المحاكاة تحسنًا في أداء النظام من حيث التحكم؛ إذ يمكننا توفير الطاقة الفعالة المطلوبة من طرف مسير الشبكة دون تجاوز طاقته القصوى. وفي الأخير، تم اختبار متانة الاستراتيجية المقترحة بنجاح في ظروف تشغيل مختلفة.

كلمات مفتاحية: نظام كهروضوئي، خوارزمية "التشويش والمراقبة" (P&O)، مُتحكِّم منطقي ضبابي، نمطي بدون تتبع أو تتبع نقطة الاستطاعة العظمى، تحكم متين.

Résumé :

Ce mémoire porte sur l'amélioration de la performance d'un système photovoltaïque (PV) connecté au réseau en utilisant la logique floue. Tout d’abord, le système PV est présenté, incluant son principe de fonctionnement, ses composants clés et son intégration au réseau. Ensuite, l'algorithme Perturb and Observe (P&O) est utilisé pour chercher le point de la puissance maximale (MPP), où ses limites sont abordées. De plus, un algorithme intelligent basé sur la logique floue est également proposé pour contrôler et gérer l'énergie du système PV étudié en deux modes sans et avec MPPT. Les résultats de simulation ont démontré une amélioration de sa performance en termes de contrôle, on peut fournir de l'énergie demandée par le gestionnaire de réseau sans dépasser sa puissance maximale. A la fin, la robustesse de la stratégie proposée est également testée avec succès pour différentes conditions de fonctionnement.

Mots-clés : Système PV, Algorithme P&O MPPT, Contrôleur à logique floue, Modes avec et sans MPPT, Contrôle robuste.

Abstract:

This thesis focuses on performance enhancement of a grid-connected photovoltaic (PV) system using fuzzy logic technique. Firstly, a general presentation of the PV system, including its principle operating, key components, and grid integration has been presented. Then, Perturb and Observe (P&O) algorithm is used to extract the Maximum Power Point (MPP), where its limitations are discussed. In addition, a fuzzy logic-based intelligent algorithm is proposed to control and manage the studied PV system energy for both non-MPPT and MPPT modes. Simulation results demonstrated that its performance is improved in terms of control, it can deliver the energy demanded by the grid manager without exceeding its maximum power. Finally, the robustness of the proposed strategy is successfully tested under various operating conditions.

Keywords: PV system, P&O MPPT algorithm, Fuzzy logic controller, Non-MPPT and MPPT modes, Robust control.

Acronyms

AC	Alternative Current
AI	Artificial Intelligence
D	Duty Cycle
DC	Direct Current
E	Insolation (w/m^2)
FLC	Fuzzy Logic Control
G	Solar irradiance
GPV	Photovoltaic Generator
I	Current (Ampere)
I_{nC}	Incremental Conductance
I-V	Current-Voltage (A-V)
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
P_{max}	Maximum Power (Watt)
PV	Photovoltaic
P-V	Power-Voltage (W-V)
PWM	Pulse Width Modulation
V	Voltag (Volt)

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General Introduction

Renewable Energy and Sustainable Development Renewable energy resources are clean and environmentally friendly. They can provide many immediate environmental benefits by avoiding the emission of greenhouse gases and can help conserve fossil resources as electricity supply for future generations. Among these renewable energy resources, photovoltaic energy generation is the current subject of much commercial and academic interest. In particular, grid-connected PV system have increased and expected to grow rapidly in future due to several advantages such as ease of installation, noiseless operation, safer operation with lower operational costs, and environmental benefit [1], [2] and [3].

In spite of numerous advantages of PVSs (Photovoltaic Systems) connected to the utility grid through power electronics converters, it is necessary to control the grid current during normal/faulty conditions and ensure grid synchronization [4].

Various control techniques had been developed in the literature for MPPT power production using a SECS which can be divided into two types: classical methods, such as Perturbation and Observation (P&O), Incremental Conductance (IC), Pilot Cell (PC), and Constant-Voltage Constant-Current (CVCC); and artificial intelligent techniques, Neural Networks (NNs), Fuzzy Logic (FL), Neural-Fuzzy (NF), Genetic Algorithms (GAs), Particle Swam Optimism (PSO) and Sliding Mode (SM) [5]–[8].

In this work, a boost chopper has been controlled by employing a Perturb and Observe (P&O) algorithm suggested in [8] to operate the studied PV system in the MPPT mode during grid climatic parameters fluctuations. In addition, an online fuzzy logic controller is proposed to ensure a control of the PV generator active power injected to the electrical grid. As a result, the grid connected PV system can be operated in both non-MPPT and MPPT modes and inject any power level requested by the grid manager into the power electrical grid without exceeding the whole system power capacity.

The present work is organized as follows: the first chapter provides a comprehensive overview of PV technologies and grid integration challenges; the second chapter reviews state-of-the-art AI techniques applied in renewable energy systems, and the final chapter presents simulation results, analysis, and conclusions regarding the system's improved performance.

Chapter I Solar Photovoltaic Systems

I.1 Introduction

Among the most sustainable and exciting sources of renewable energy accessible today are solar ones. Because of its dependability, scalability, and capacity to directly convert sunlight into energy without moving parts or pollutants, photovoltaic (PV) systems have grown to be the most often utilized among the several technologies designed to capture solar power [1]. Comprising solar panels, inverters, and occasionally batteries, a PV system is made from parts that cooperate to produce and distribute sustainable electrical energy.

Any PV system consists mostly on the solar cell, a semiconductor device driven by the photovoltaic phenomenon whereby sunlight's photons stimulate electrons in the material to produce electric current [2]. Though basic in theory, this process is influenced by several environmental and material elements including irradiance, temperature, and cell structure. Improving the efficiency and design of solar energy systems depends on a knowledge of these elements.

The basic ideas of photovoltaic technology are introduced in this chapter. It gives a general picture of how solar cells operate, addresses the components and varieties of PV systems, and highlights the key benefits and drawbacks of their application. Understanding the sophisticated control and optimization techniques covered in later chapters—especially those pertaining to Maximum Power Point Tracking (MPPT— depends on this background.)

I.2 Energy photovoltaic

Direct solar panel conversion of light radiation from the sun into electricity produces photovoltaic solar energy. Either heat to water or air or electricity utilized straight or spread through distribution stations is created. Historically in 1883, American Charles Fritts succeeds to create the first photovoltaic cell a wafer of selenium (semi-conductor material) covered with extremely fine layers of gold. And 1973 the University of DELWAY opens the first residence running on photovoltaic cells. [3]

I.2.1 Working principle

In the realm of electronics, a solar cell is a component that is capable of generating electricity. The conversion of solar radiation into electric current by means of a photovoltaic panel or units is the fundamental principle underlying the manufacturing of products using photovoltaic technology. To do this, a potential difference is created between the positive electrode and the negative electrode. This difference in potential enables the electrons to rotate and continue to produce an electric current, which is the fundamental principle behind the operation of a battery. The electrons that are already present. In silicon, it is one of the semi-conductors that form photovoltaic cells, with the property of moving under the influence of sunlight, and to adjust the directions of these electrons and to produce electricity, an effort must be produced in addition to solar induction by making a potential difference between the positive and negative poles, and this effort is created by taking silicon to some additional atoms (activators) Which contain more or fewer electrons than silicon, (N-type negative dopants) because the cell layer exposed to light contains phosphorous atoms that are more than one electron than silicon, (P-positive dopants) because boron atoms are present in the cell layer that is less than one electron Concerning Silicon Cells are surrounded by conductors on all sides. As soon as the sunlight reaches the N-doped layer, the electrons begin to move, which results in the creation of an electric current that is then collected by the conductors (Figure I.1) [3].

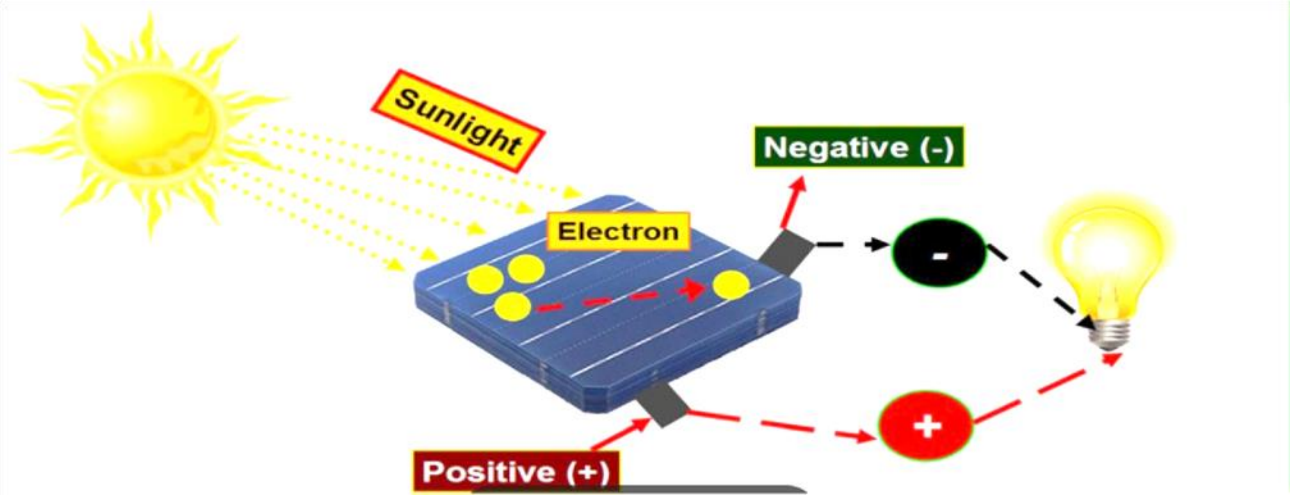


Figure I-1 working principal of cell photovoltaic [5]

I.2.2 Different Types

Solar PV with storage systems fall into three categories: grid-connected without battery, grid/hybrid, and off-grid. Each form has pros and cons.

I.2.2.1 System grid connected with battery

The predominant system has consumers linked to the network who utilize it but are susceptible to frequent power outages, leading them to adapt to intermittent power loss while depending on an electrical system that functions as a charger for storage. Mechanism for anticipating power disruptions and subsequently utilizing stored energy as a substitute. One of its disadvantages is that it is significantly more expensive than the platforms due to additional components, such as the charging control unit, and sub-panels that accommodate essential loads like lighting and backup systems for use during power outages. However, it is a system that facilitates energy utilization during peak demand periods (*Figure I.2*). [6]

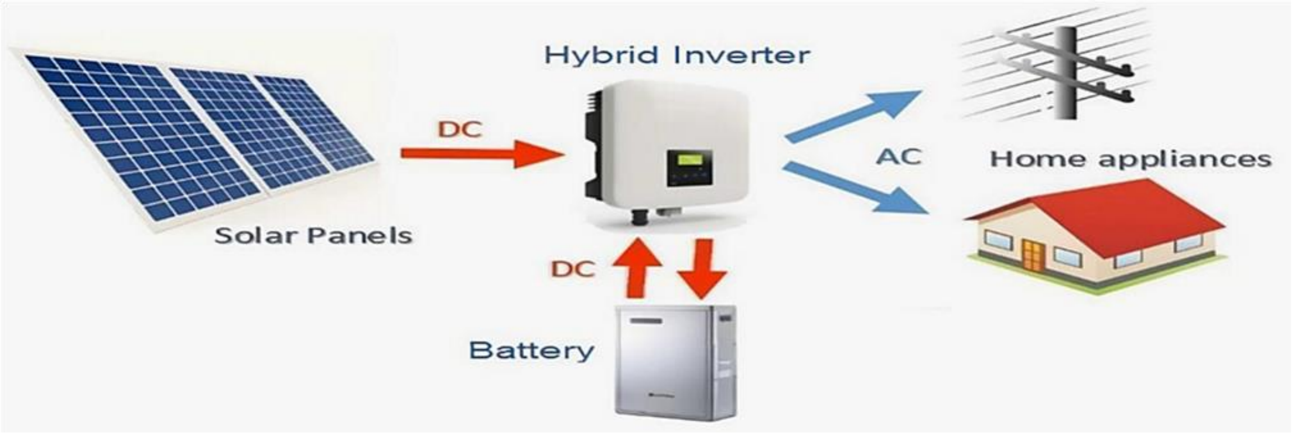


Figure I-2 System grid/hybrid with battery [7]

I.2.2.2 System grid-connected without battery

Ideal for linked users looking to power their homes with solar energy, this simple installation includes a standard networked reflector and does not include a storage system (battery). The primary goal of this system is to lower the energy bill and take advantage of solar energy, therefore it is easy to design and very cost-effective due to its low component count and large production, which is achieved by sending the excess energy back to the grid for a payment (*Figure I.3*). [7]

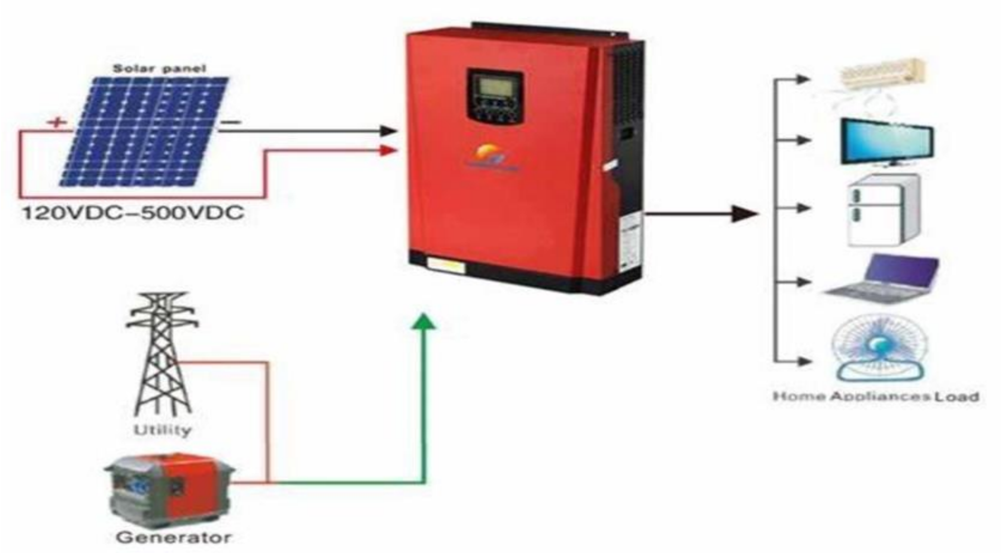


Figure I-3 System grid-connected without battery [8]

I.2.2.3 System off-grid

This approach accommodates consumers facing challenges in network connectivity or elevated power supply costs owing to their geographical location, but it does not imply total network disruptions. It is referred to as an auxiliary source system due to its incorporation of many charging sources, such as Generators that facilitate battery charging maintenance during periods of inadequate output from renewable sources, with variability contingent upon weather conditions. Factors such as solar and wind. A downside of this system is its design to accommodate 100% of power requirements, rendering it more costly than a grid-connected system due to its substantial components (*Figure I.4*). [3]

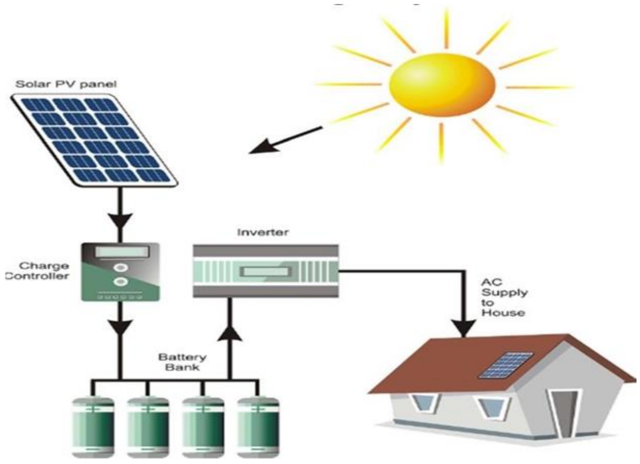


Figure I-4 System off-grid [9]

I.3 Advantages and drawback

I.3.1 Advantages

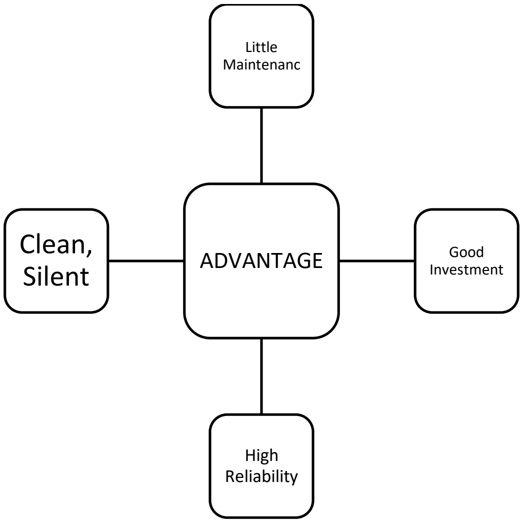


Figure I-5 the advantages of PV system

A. **Exceptional reliability:** the dependability and longevity of the installation.

B. **Renewable energy source:** Solar energy is derived from the sun, making it a renewable and clean resource. It is free and environmentally friendly, causing no ecological disruption aside from the spatial requirements of huge installations.

C. **Adaptation:** the inherent characteristic of photovoltaic panels facilitates straightforward and versatile installation in remote locations, where cabling connections to traditional electrical grids are notably challenging and costly. It can be deployed in any location where sunlight is available.

D. **The Operating cost is very low:** due to less maintenance and requires no fuel or transportation, even negligible compared to other renewable energy system. And as soon as your solar energy system is installed, you can start producing electricity. Then your bills will go down. [10]

I.3.2 Drawback

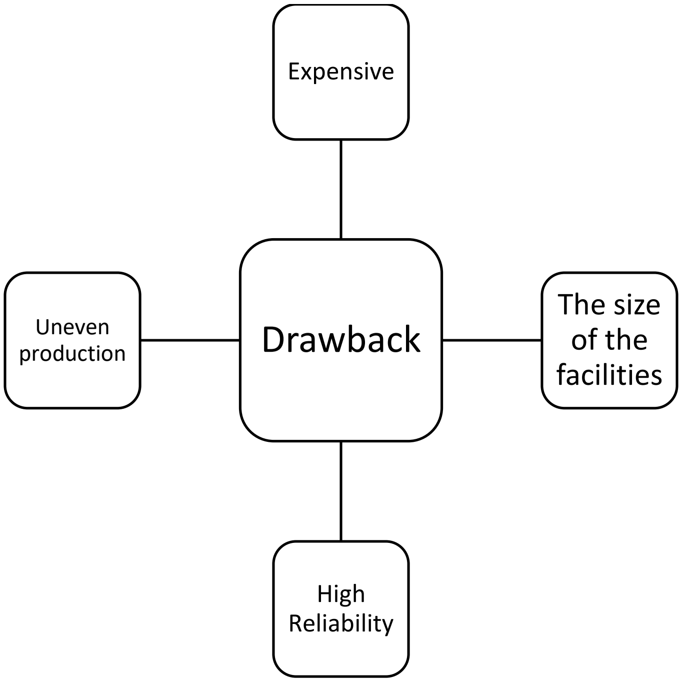


Figure I-6 The drawback of PV system

- Expensive, high-tech solar unit manufacture that results in extremely high cost in addition to generator cost depending on form (battery).
- In the present, electric energy storage still presents numerous issues.
- Uneven products since climate influences them.
- Although their modest power needs in isolated places make electric generators less competitive than diesel generators, they become more economical particularly in isolated areas where fuel transportation is quite expensive. [11]

I.4 Classification of photovoltaic systems

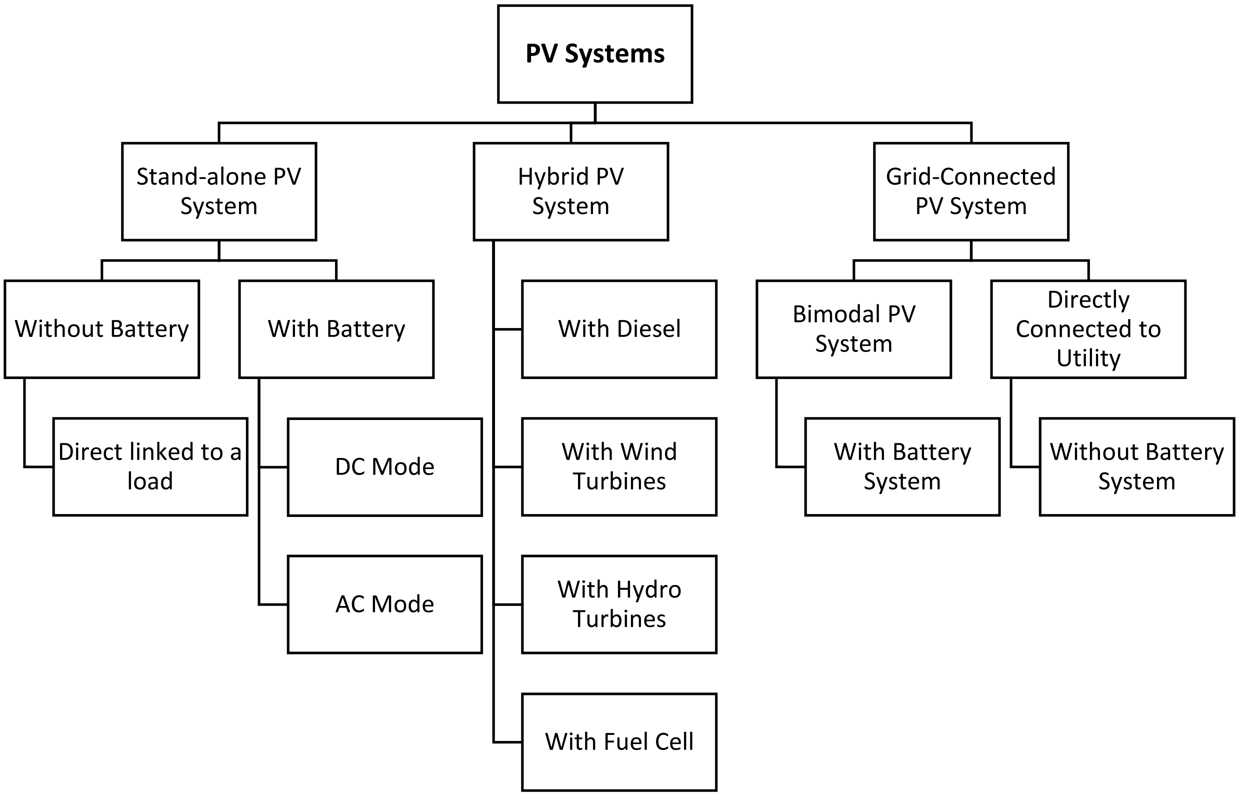


Figure I-7 Classification of photovoltaic systems [12]

I.4.1 Standalone photovoltaic system

The photovoltaic system totally depends on other energy sources that provide the customer with electricity. Usually, this technology stores energy using batteries. One self-contained PV system example is shown in (Figure 1.8)

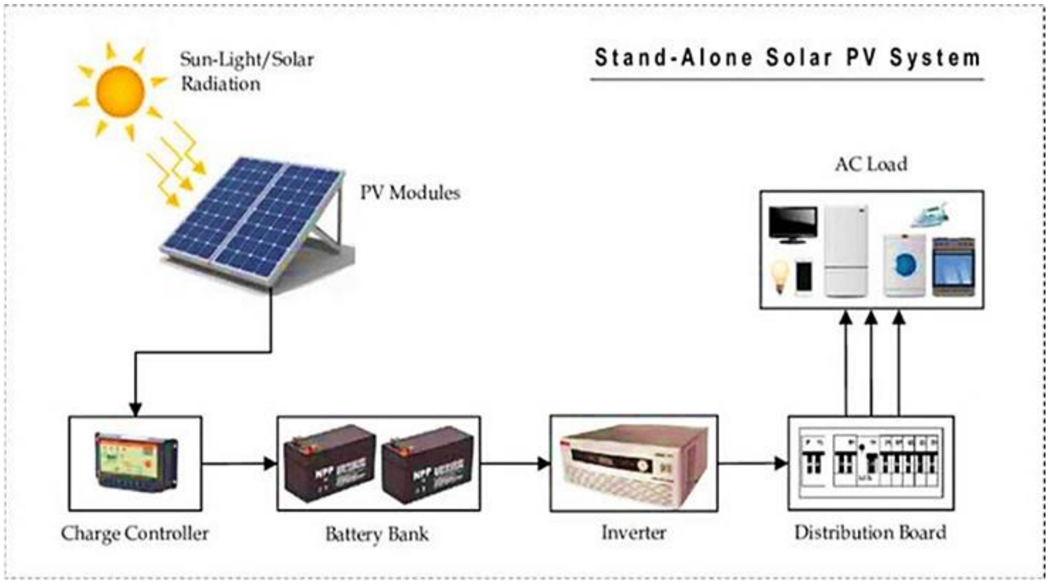


Figure I-8 Standalone photovoltaic system [13]

I.4.2 Autonomous system with battery

The battery uses the PV kit as its charger. One can then use the electricity at any moment. For street lighting, for instance, this technique is rather appropriate since energy is required when daylight is lacking. [3]

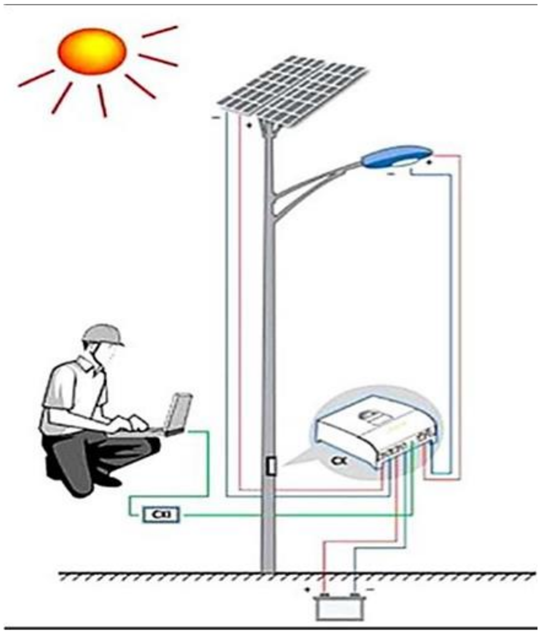


Figure I-9 Autonomous system with battery [14]

I.4.3 Autonomous system without battery

In these systems without a battery, there is the possibility of using some form of storage for example:

Pumping: storage by the water tank

Refrigeration: cold storage (ice storage or eutectic) [3]

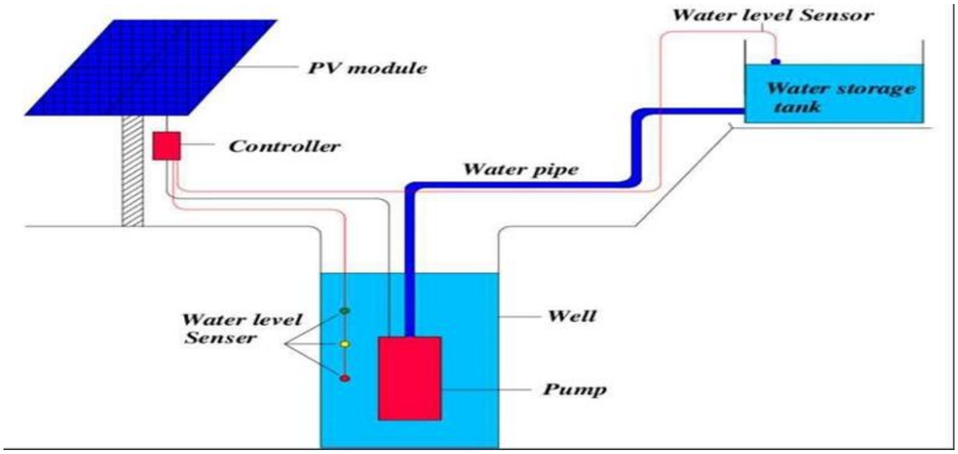


Figure I-10 Schematic diagram of a pumping system over the sun [15]

I.4.4 Hybrid systems

As it is shown in (Figure I.12), the hybrid system comprises of a PV generator coupled with a wind turbine or a fuel-powered generator set (back-up module), or two at a time. We say pairing if there are two or more renewable energies used together. [16]

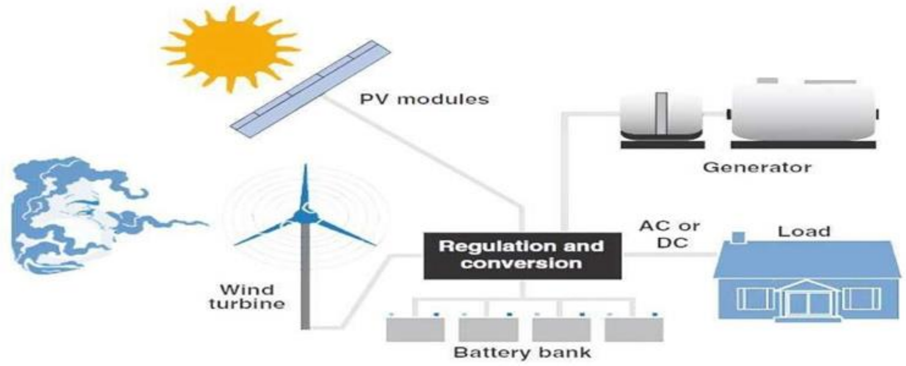


Figure I-11 Hybrid Power System [17]

I.4.5 Grid-connected photovoltaic system

Grid PV System, Solar PV Power Generation System coupled to the electrical network. A grid-connected photovoltaic system comprises of one inverter or numerous inverters, a power conditioning unit, and network connection equipment together with solar panels. The excess from the on-site energy consumption for the product is transmitted to the network supplying residences on sunless days or at night. [17]

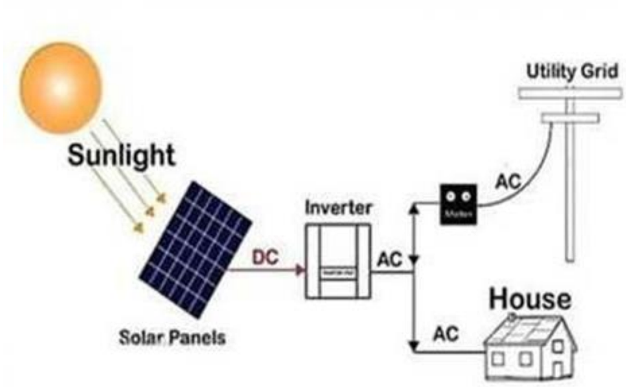


Figure I-12 Represents a grid-connected PV system [18]

I.5 Integration of photovoltaic systems in different categories

Solar energy among other alternative energy sources is becoming more and more popular since many businesses and sectors have noticed them.

I.5.1 Industry sector

Some of the advantages that industrial companies get by installing solar photovoltaic cells

I.5.1.1 Reduced electricity bills

Usually roughly 20% less than traditional electricity, solar power presents a reasonably affordable alternative while electricity rates are rising. For companies, particularly warehouses where up to 15% of overall running expenses are related to power, solar energy offers a consistent, fixed-cost substitute with a 25 to 30 year lifespan. Along with lowering long-term expenses, it helps balance energy use. Solar systems also fit businesses with high energy consumption from interior and outdoor equipment and lights as they demand less maintenance and minimum monitoring.

Investing in the future of the earth, industrial solar energy systems help to preserve non-renewable energy sources and safeguard the surroundings.

I.5.1.2 Support from local authorities in some countries

Support from local authorities in some nations: The government of some nations grants tax credits to those who install rooftop solar panels, either for personal or commercial use, therefore motivating individuals to embrace solar energy. Local governments are increasingly endorsing renewable energy businesses as means of supporting a green metropolitan economy. [19]

I.5.2 In education and the religious place

Muslims gather to pray in mosques five times a day because the sun rules these times, it changes throughout the year. The relatively large size of mosque roofs and their ubiquity throughout the Islamic world make them ideal candidates for solar photovoltaic (PV) installations.

I.5.3 Transport

How can we use solar energy in transportation?

I.5.3.1 BUS

Launched in Adelaide, Australia in 2013, Tindo is the first solar-powered bus ever. Although the bus itself runs entirely on electricity and generates zero emissions, it does not have solar panels onboard. It runs on a battery kept charged at a central bus station run under solar power. Solar energy also finds usage in bus terminals, where panels over bus stops gather daytime sunshine. Nightly digital information boards and billboards run on the stored energy as well.

Figure I-13 Tindo buses [20]

I.5.3.2 Planes

Solar Impulse, the only aircraft capable of flying day and night using only solar energy, has its current goal to make the first solar flight around the world.

I.6 Conclusion

This chapter investigated the photovoltaic energy conversion principle, therefore clarifying how photovoltaic cells turn solar energy into electricity. We also looked at several photovoltaic system layouts, stressing their fit for use in isolated or distant locations cut off from the main power grid. Although these systems present interesting options for off-grid energy access, various technological and budgetary constraints make them not now economically feasible for major uses. Still, their possibility for more general use is great given ongoing technology developments and cost cuts.

Chapter II Maximum Power Point Tracking (MPPT) Techniques

II.1 Introduction

Highly reliant on external factors like irradiation and temperature, photovoltaic (PV) systems produce continual fluctuation in their maximum power point (MPP). Maximum Power Point Tracking (MPPT) techniques are applied to real-time operating point adjustment of the PV array in order to sustain ideal energy production.

Usually combined with DC-DC converters, these methods let the system dynamically adjust to changing conditions. By up to 30% in non-ideal circumstances, MPPT can increase system efficiency and aid to reduce power losses [21].

From simple algorithms like Perturb and Observe (P&O) to sophisticated ones based on fuzzy logic and artificial intelligence, several MPPT techniques are available. The working ideas of MPPT are covered in this chapter together with a comparison of several approaches depending on performance and flexibility.

II.2 Principle of MPPT operation

The fundamental principle of the MPPT regulator is to extract the maximum electrical energy from solar cells by operating them at their most efficient voltage, known as the Maximum Power Point (MPP). Subsequently, the regulator works to reduce the total panel voltage to match the charging voltage and obtain the maximum charging current for the battery. Additionally, it can efficiently power DC electrical loads.

Depending on the running conditions, MPPT greatly increases the efficiency of PV systems by gains ranging from 10% to 25% [22].

II.3 DC-DC converter modeling for MPPT

The three basic switching power supply topologies most used are buck, boost, and buck-boost converters. These configurations are non-isolated, hence the ground reference of the input and output voltages is shared. For uses needing galvanic isolation, however, separate versions of these fundamental topologies also exist.

Key component arrangement and interaction that of the switching device(s), output inductor, and output capacitor are described by a power supply topology. Two main conduction modes are Continuous Inductor Current Mode (CCM) and Discontinuous Inductor Current Mode (DCM), for DC-DC converters. Under steady-state operation in CCM, the inductor current stays constantly flowing over the whole switching cycle. DCM begins at zero, increases to a peak, and returns to zero in every cycle; it is distinguished by the inductor current dropping to zero for a part of the cycle.

Usually preferable is keeping a single conduction mode across the converter's whole operational range since the dynamic response of the power stage differs significantly between CCM and DCM. Usually found in (Figures II.1 to II.3) are the simplified circuit designs for the buck, boost, and buck-boost converters. Usually consisting of an input capacitor, an output capacitor, a power MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor), a diode, and an inductor each power stage consists [23].

II.3.1 Buck converter

Figure II.1 presents a condensed electric schematic of a simple buck converter. The power supply of the switch on connects to the inductor and the diode is reverse polarized. The inductor L gains collecting energy as a current pass through it. The energy contained in the inductor is output through the diode D when the transistor shuts off. Operating as a step-down system, DC-DC buck converters will step down the high input voltage to the low output voltage, whose magnitude is always smaller than that of the input voltage. By including the LC low pass filter to the fundamental circuit of this converter, this design aims to generate a solely DC output. From a high PV array voltage, this DC-DC buck converter can be coupled to either low voltage DC load or battery bank.

The dynamics of the converter in one switching period is represented by the following system [23]:

$$\begin{aligned} C_1 \frac{dv_{in}(t)}{dt} &= i_{in}\,(t) - d i_L\,(t) \\ C_2 \frac{dv_{out}(t)}{dt} &= i_L\,(t) - i_{out}\,(t) \\ L \frac{d_{iL}(t)}{dt} &= d v_{in}\,(t) - v_{out}\,(t) - R_L i_L\,(t) \end{aligned} \tag{II.1}$$

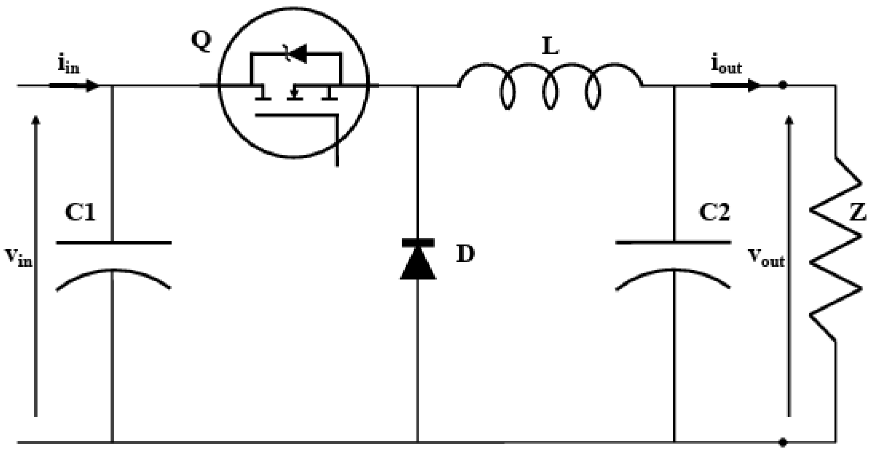


Figure II-1 Electrical circuit of a buck converter [23]

II.3.2 Boost converter

The boost converter in Fig.II.2 is another simple switched-mode converter. This converter takes in a voltage and gives out a higher voltage. It's also known as the step-up converter. A control signal that changes the width of the pulse tells the transistor when to turn on and off. When the transistor is on, the voltage across L is the same asV_{in}, and the current in the inductor rises in a straight line. The inductor current runs through the diode and charges the output capacitor when the transistor is off. You can also talk about the boost converter's job in terms of energy balance: The inductor gets energy when the transistor is in the "on" state. This energy is then sent to the output capacitor while the transistor is in its blocking phase. The voltage coming in is always less than the voltage going out.

The dynamics of the converter in one switching period is represented by the following system [23]:

$$\begin{aligned} C_1 \frac{dv_{in}(t)}{dt} &= i_{in}(t) - d i_L\,(t) \\ C_2 \frac{dv_{out}(t)}{dt} &= (1-d)\, i_L(t) - i_{out}\,(t) \\ L \frac{d_{iL}(t)}{dt} &= v_{in}(t) - (1-d)\, v_{out}(t) - R_L i_L\,(t) \end{aligned} \qquad \text{(II.2)}$$

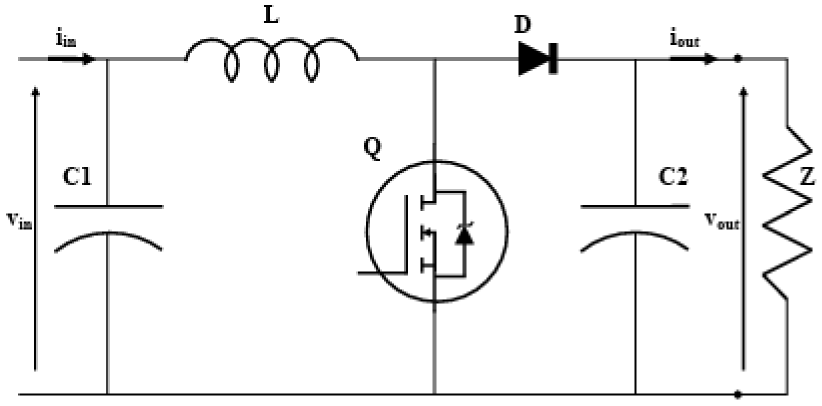


Figure II-2 Electrical circuit of a boost converter [23]

II.3.3 Buck-boost converter

Fig II.3 shows a simplified electric schematic of a basic inverting buck-boost converter. During the closing time $d\,T_s$ of the transistor, the source voltage V_{in} is applied across the inductor L, which results in accumulating energy in the inductor. During the opening period $(1-d)T_s$, the diode D is forward-biased and the voltage of the inductance is applied to the load Z. The current flows anticlockwise through the diode D.

Thus, the output voltage will be negative.

The dynamics of the converter in one switching period is represented by the following [23]:

$$\begin{cases} C_1 \dfrac{dv_{in}(t)}{dt} = i_{in}(t) - d i_L(t) \\ C_2 \dfrac{dv_{out}(t)}{dt} = -(1-d) i_L(t) - i_{out}(t) \\ L \dfrac{d_{iL}(t)}{dt} = d v_{in}(t) + (1-d) v_{out}(t) - R_L i_L(t) \end{cases} \tag{II.3}$$

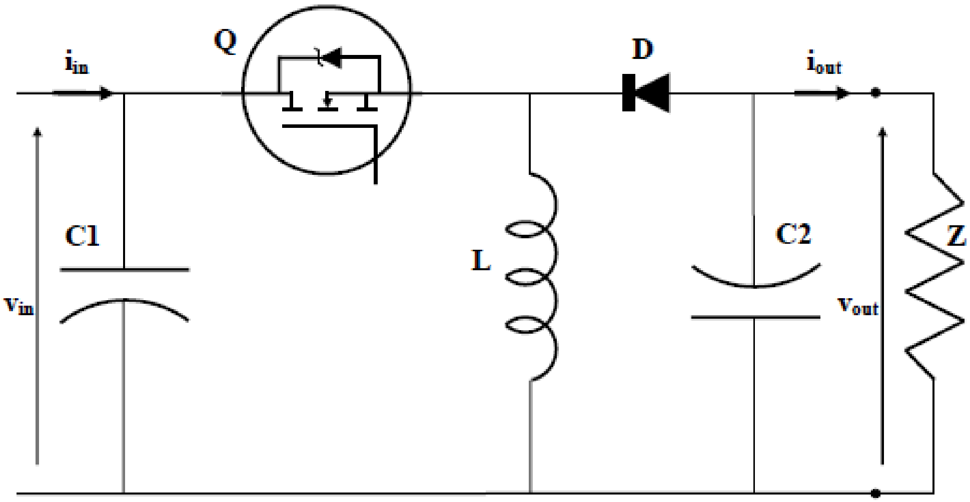


Figure II-3 Electrical circuit of a buck-boost converter [23]

II.4 PV System characteristics relevant to MPPT

Correct implementation and performance of Maximum Power Point Tracking (MPPT) approaches depend on an awareness of the electrical behavior of photovoltaic (PV) systems. Highly sensitive to external events, PV modules show non-linear current-voltage (I-V) and power-voltage (P-V) characteristics. These properties define the Maximum Power Point (MPP) on the curve and so directly affect the efficiency of any MPPT control system. Without a good understanding of these dynamic characteristics, particularly under real-world operating conditions, MPPT algorithms may fail to track the optimal point, therefore causing notable energy losses [24]. The operation and responsiveness of the MPPT controller is examined in the following subsection under environmental parameters like irradiation and temperature.

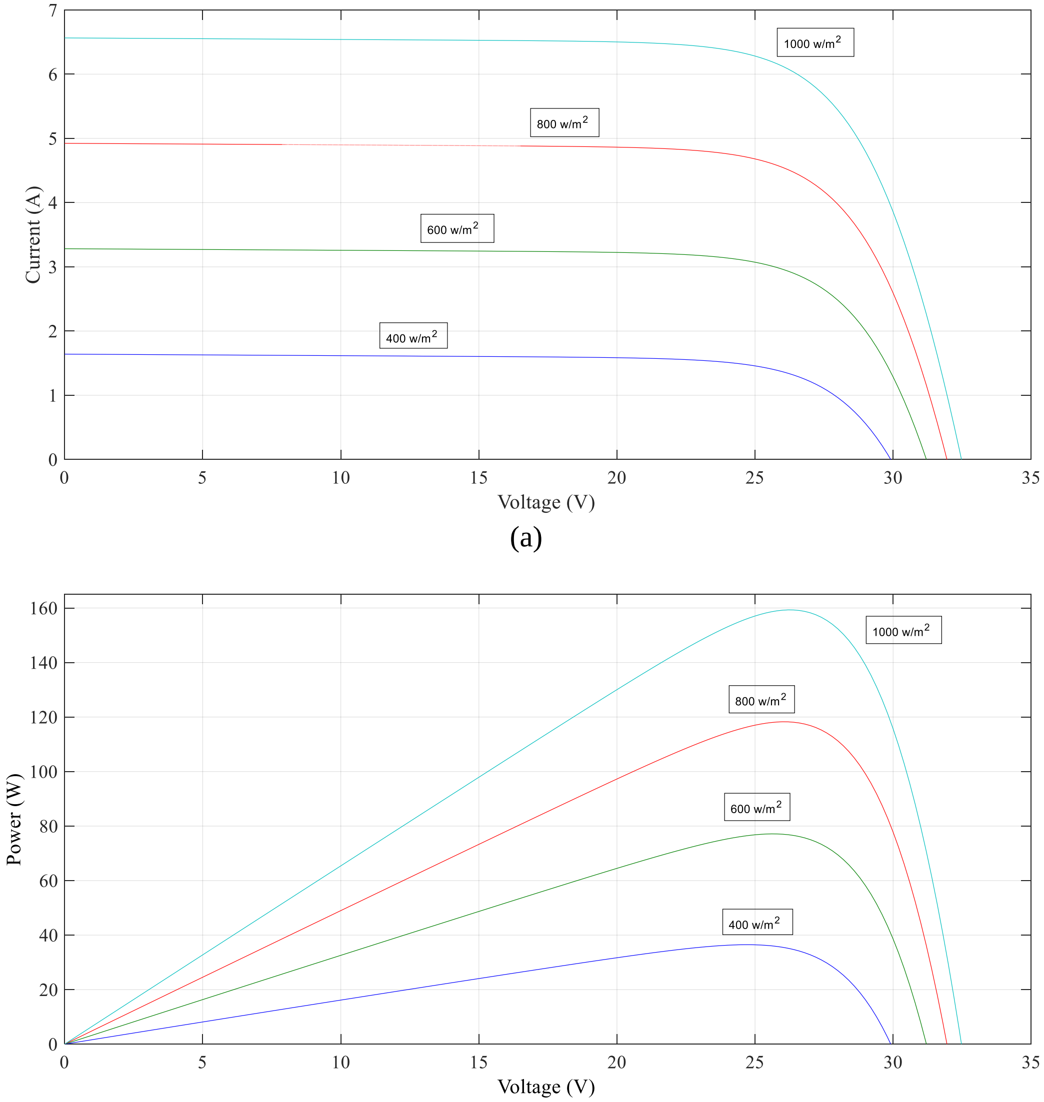
II.4.1 Effects of environmental factors on the MPPT regulator

The following environmental elements have a substantial impact on the solar cell's characteristics:

- ***Insolation***
- ***Temperature***

II.4.1.1 Impact of insolation

A photovoltaic cell's performance is substantially affected by the solar irradiation (insolation). The solar cell's short-circuit current (I_{sc}) falls almost exactly as insolation drops, therefore producing a clear drop in total output power. Furthermore, shifting with changing irradiation levels is the maximum power point (MPP), which emphasizes the need of dynamic adjustment using MPPT systems to guarantee effective energy harvesting under different environmental conditions. [25]



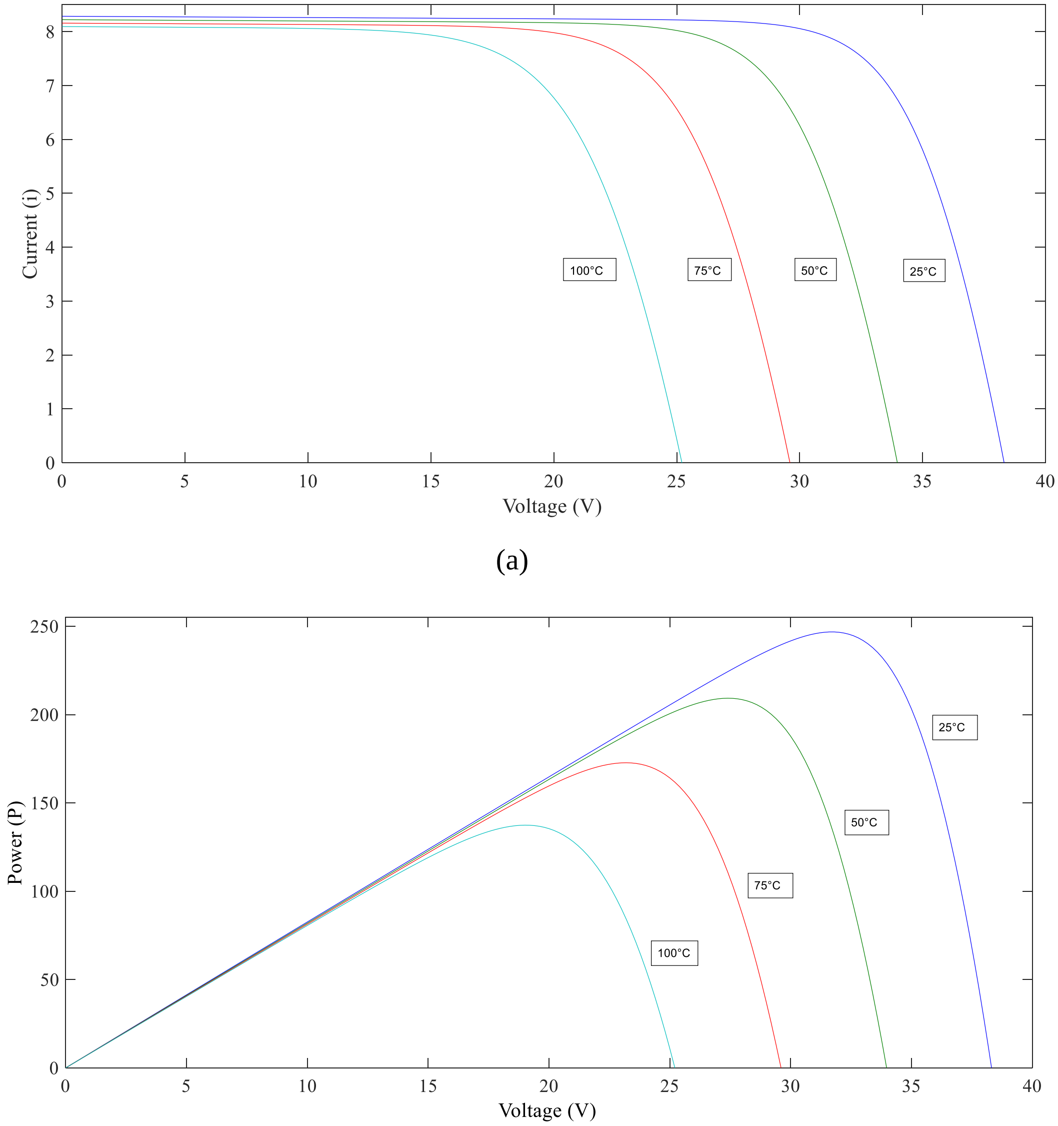
(a)

(b)

Figure II-4 Solar I-V and P-V Characteristics with Different Insolation Levels and Constant Temperature [25]

II.4.1.2 Impact of temperature

Another crucial determinant of solar cell electrical performance is temperature. While the short-circuit current (I_{sc}) slightly logarithmic increase as temperature rises, the open-circuit voltage (V_{oc}) often falls dramatically. But the most important effect of the voltage drop is that it causes the power output to drop generally. This inverse link between temperature and PV efficiency emphasizes the requirement of MPPT controllers to change in high-temperature environments to reduce power losses [25].



(a)

(b)

Figure II-5 II-6 Solar I-V and P-V Characteristics at Different Operating Temperatures with Constant Insolation [25]

All things considered, environmental factors including sun irradiation and temperature directly affect the electrical properties of photovoltaic systems especially the I-V and P-V curves. These elements lead to constant changes in the location of the Maximum Power Point, therefore rendering stationary operation ineffective. Consequently, the design and application of dependable MPPT algorithms depend on a thorough knowledge of how these factors influence PV performance. Precise tracking of the MPP under different climatic conditions guarantees best energy conversion, improves general system efficiency, and helps solar energy systems to be long-term viable.

II.5 MPPT algorithms

By enabling the most potential power under varying environmental conditions, MPPT algorithms are fundamental in photovoltaic (PV) systems. These methods are applied to constantly modify the operating point to follow the Maximum Power Point (MPP) of a solar panel since factors like sunshine and temperature affect its MPP.

There have been developed several MPPT methods, each with benefits and cons. While some employ more advanced techniques including fuzzy logic or artificial intelligence to increase tracking speed and accuracy, others are basic and extensively used such Perturb and Observe (P&O) and Incremental Conductance.

The most often used MPPT techniques are introduced in this part together with their working principles and variations from one another.

II.5.1 Perturb and Observe (P&O)

Thanks to its simplicity of implementation, low computing demand, and cheap hardware requirements, the Perturb and Observe (P&O) approach is among the most often used MPPT techniques in photovoltaic (PV) systems. It finds the direction toward the maximum power point (MPP) by varying the operational voltage (or duty cycle of the DC-DC converter) and tracking the subsequent change in output power.

- **Operating Principle:**

The algorithm relies on the fact that the slope of the power-voltage (P–V) curve of a PV module is positive when operating to the left of the MPP, and negative when to the right. The control system perturbs the voltage and observes the change in output power:

- If the power increases following a perturbation, the system continues perturbing in the same direction.
- If the power decreases, the perturbation direction is reversed.

Mathematically, this behavior is based on the sign of the derivative:

$$\frac{\Delta P}{\Delta V} = \begin{cases} > 0 & \rightarrow \text{ Increase V} \\ < 0 & \rightarrow \text{Decrease V} \end{cases} \qquad \text{(II.4)}$$

This perturb-and-observe loop is repeated continuously to maintain the system close to the MPP under varying environmental conditions [26]

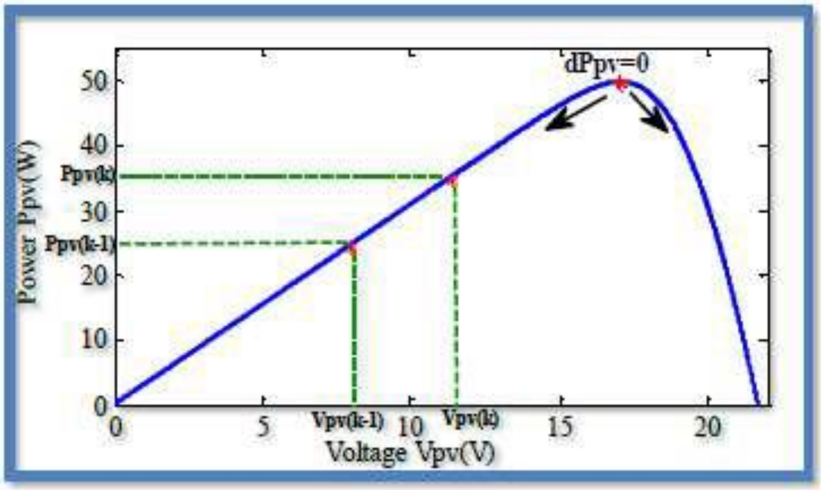


Figure II-7 characteristic for the P&O MPPT algorithm [27]

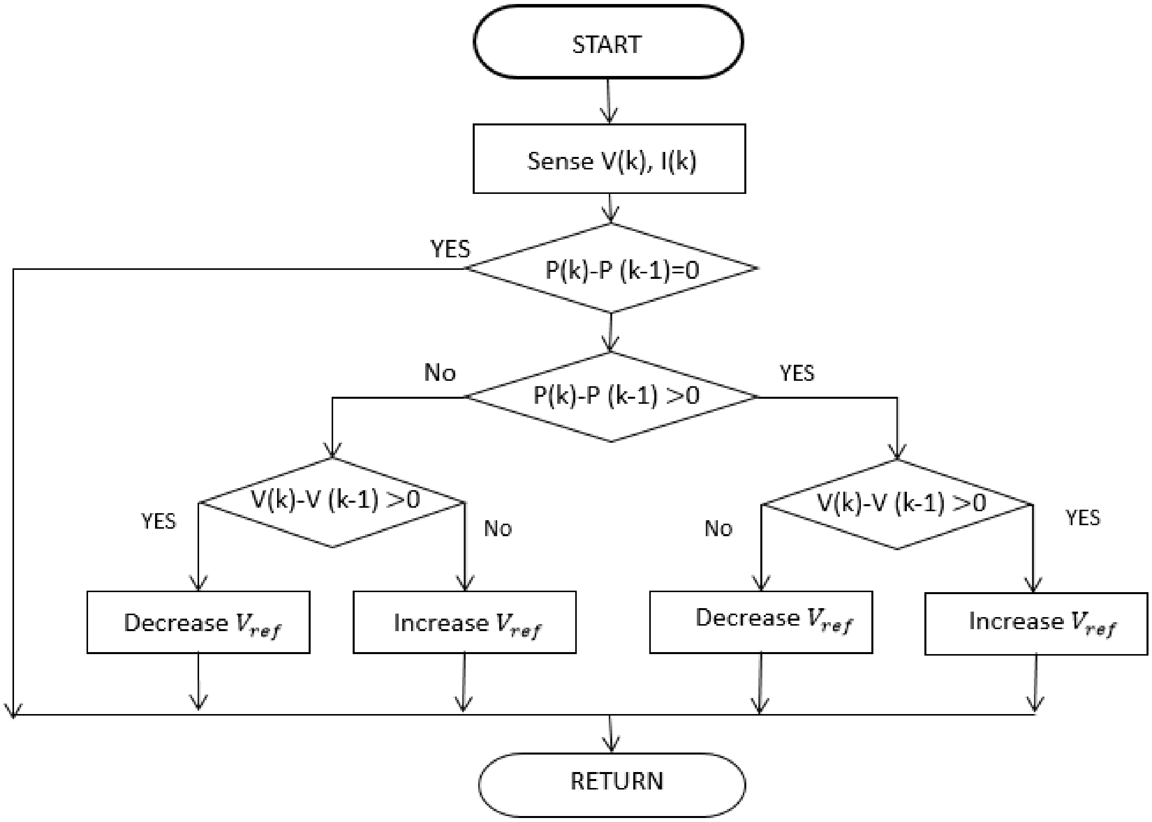


Figure II-8 MPPT algorithm disturb and observes (P&O) [27]

In the event that the amount of sunshine increases or decreases abruptly, the power of the panel will also increase or decrease based on the sunshine conditions. The algorithm responds as though the increase is the result of the earlier disruption, so it keeps going in the same direction which is incorrect and deviates from the actual point of maximum power. And all of this results in power losses and delays in rethinking the algorithm during abrupt changes in operating conditions.

II.5.2 Incremental Conductance method

The IncCond algorithm is based on the fact that the slope of the curve power vs. voltage of the PV module is zero at the MPP. [28]

The output voltage and current from the PV array are monitored upon which the MPPT controller relies to calculate the conductance and incremental conductance and to make its decision (to increase or decrease the duty ratio output).The output power Of PV array can be expressed as:$P_{pv} = I_{pv} \times V_{pv}$ .Then, the derivative of the product yields:

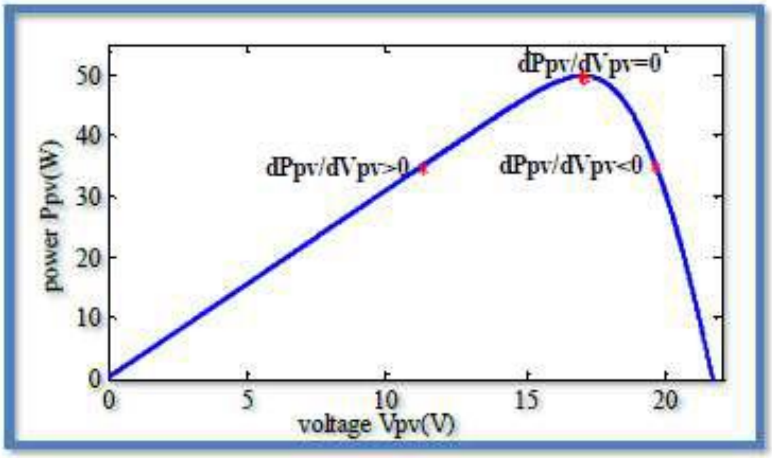


Figure II-9 characteristic for the Incremental Conductance MPPT algorithm

$$\begin{cases} \dfrac{dP}{dV} = 0 \quad at\ MPP \\ \dfrac{dP}{dV} > 0\ at\ the\ left\ of\ MPP \\ \dfrac{dP}{dV} < 0\ At\ the\ right\ of\ MPP \end{cases} \tag{II.5}$$

Because:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \tag{II.6}$$

$$\begin{cases} \frac{\Delta I}{\Delta V} = -\frac{I}{V} \text{ at MPP} \\ \frac{\Delta I}{\Delta V} > -\frac{I}{V} \text{ At the left of MPP} \\ \frac{\Delta I}{\Delta V} < -\frac{I}{V} \text{ At the right of MPP} \end{cases} \tag{II.7}$$

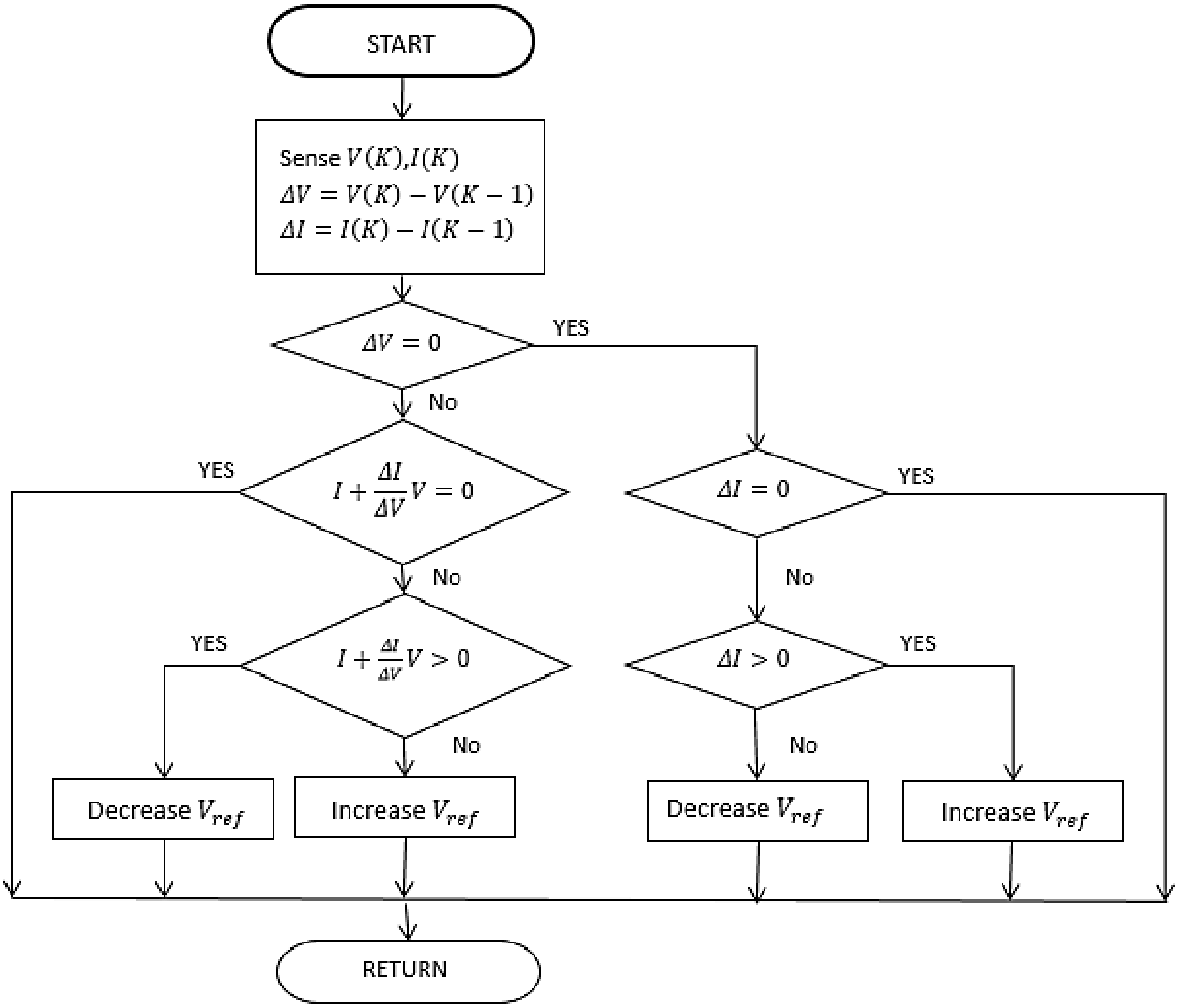


Figure II-10 MPPT control algorithme Conductance incrémente méthode [27]

II.5.2.1 Improved conductance increment method

The conductance increment method can be made better by adding a PI corrector or by first bringing the operating point close to the MPP, and then using the Conductance Incrementing algorithm to track the MPP precisely in a second step.

II.6 Fuzzy logic

II.6.1 Definition of fuzzy logic

This section presents the general principles and foundational theory of fuzzy logic, emphasizing its application in the Maximum Power Point Tracking (MPPT) of photovoltaic (PV) systems. Fuzzy logic provides an effective control strategy for systems characterized by nonlinearity and uncertainty, which are inherent in solar energy conversion due to environmental variations such as irradiance and temperature.

Fuzzy logic controller structure is based on fuzzy sets where a variable is a member of one or more sets with a specified degree of membership. Benefits of using Fuzzy logic are; it allows us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague information such as resistive load is connected to the PV module through the buck boost dc-dc converter [29]. The block diagram of MPPT based fuzzy logic control is shown in (Figure 4-2) [30].

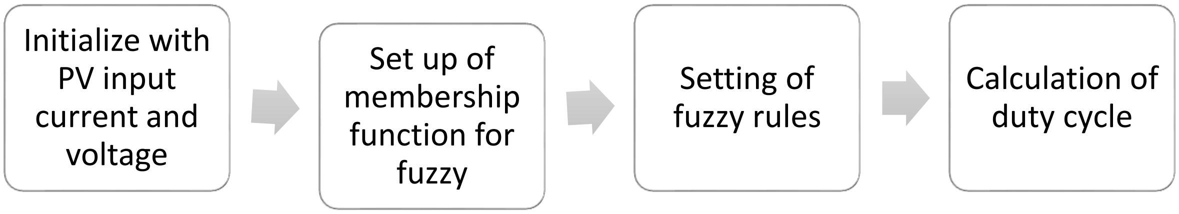


Figure II-11 Block diagram of the fuzzy logic algorithm

Also, (Figure II.10) illustrates the basic architecture of fuzzy controller which contains of the three following blocks [31]:

- Fuzzification of input variables such as the change in power (ΔP) and the change in voltage (ΔV).
- Rule-based fuzzy inference for decision-making.
- Defuzzification to generate the appropriate duty cycle for the DC-DC converter.

II.6.2 Principle and History of Fuzzy Logic

Fuzzy logic is a technique that replaces binary logic with a logic based on variables that can take, in addition to "true" or "false" values, intermediate values of "true" or "false" to a certain degree. This reflects human reasoning, which is often based on imprecise or incomplete data. For example, determining whether someone is short or tall is easy for most people, even without knowing the person's exact height. Suppose the threshold is 1.65m, and I measure 1.63m. Am I really short?

Although the word "fuzzy" generally has a negative connotation, this is not the case here.

The word "fuzzy" comes from the English term "fuzzy," which originally referred to the downy feathers covering chicks. It means indistinct, blurred, poorly defined, or unfocused, translated as "flou" in French.

In academia and technology, "fuzzy" is a technical term representing ambiguity or vagueness in human intuition rather than probability.

A brief history of fuzzy logic [32]:

- In 1965, the fuzzy concept appeared thanks to Professor Lotfi Zadeh (University of California, Berkeley). He stated that an electromechanical controller with human reasoning would perform better than a classical controller and introduced the theory of "fuzzy subsets."
- In 1973, Zadeh published a paper (IEEE Transactions on System, Man and Cybernetics), introducing the concept of linguistic variables (whose values are words, not numbers).
- In 1974, Mamdani (University of London) created an experimental fuzzy controller for controlling a steam engine.
- In 1980, Smidth and Co.A/S (Denmark) applied fuzzy logic theory to cement kiln control – the first practical implementation.
- In the 1980s, many applications emerged, especially in Japan.
- In 1987, fuzzy logic boomed in Japan (notably in Sendaï metro control), peaking in 1990.
- Today, many products bear the "fuzzy product" label.

The application of fuzzy logic in control and regulation systems is relatively recent. Since the mid-1980s [32], fuzzy control has grown, especially in Japan. It has been used to solve diverse industrial control problems in energy, transportation, machine tools, robotics, and increasingly in renewable energy applications such as MPPT in PV systems.

II.6.3 General Structure of a Fuzzy MPPT System

A fuzzy logic-based Maximum Power Point Tracking (MPPT) system typically consists of the following main components (see Figure II.11):

a) Fuzzification

This stage converts precise input variables such as the change in power and the change in voltage into fuzzy linguistic variables represented by degrees of membership. These inputs reflect the behavior of the PV system under varying environmental conditions.

b) Knowledge Base, which includes

- A database that contains the parameters of the membership functions. These functions are defined based on expert knowledge and system behavior, providing the linguistic framework required for fuzzy reasoning.
- A rule base, composed of a set of "If...Then" fuzzy rules, derived from expert insight or empirical data, that govern how the MPPT controller reacts to different input conditions. Each rule typically links one or more fuzzy premises using logical operators (AND/OR) and results in a fuzzy control action to adjust the operating point of the PV system.

c) Defuzzification

In this final step, the fuzzy outputs (control actions) are converted into a precise value, such as a duty cycle for the DC-DC converter, to drive the photovoltaic system toward its maximum power

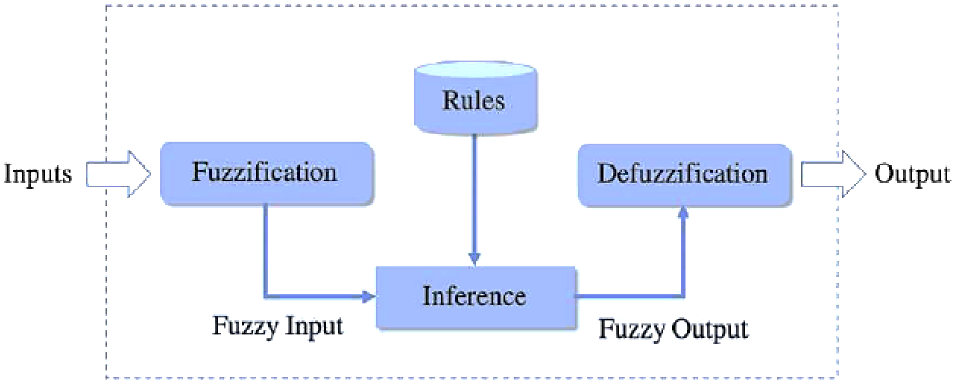


Figure II-12 Structure of fuzzy logic controller

II.6.4 Design of the Fuzzy MPPT Controller

II.6.4.1 Fuzzification

The objective of Fuzzification is to define the membership functions for the different variables that make the input variables blurred. A preliminary step is to define a maximum allowable range of variation for the input variables. The purpose of Fuzzification is to transform input variables into linguistic variables or fuzzy variables [31].

In this case, we have two input variables which are error E (k) and variation of sampling error k which are defined as follows: ΔE (k) at the moment

$$\boldsymbol{E\ (k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}} \tag{II.8}$$

$$\Delta \boldsymbol{E} = (\boldsymbol{k}) - (\boldsymbol{k} - \boldsymbol{1}) \tag{II.9}$$

Where $P(k)$ is the power of the photovoltaic generator and $V(k)$ the voltage of the photovoltaic generator therefore $E(k)$ is equal to zero at the maximum power point of the photovoltaic generator; these input variables are expressed in terms of language variables such as NG (large negative:), NP (small negative), EZ (equal to zero), PP (small positive), and PG (large positive).

II.6.4.2 Inference method

The tuning strategy depends on the inferences adopted. They bind the input variables to an output variable. This step consists of defining a logical relationship between the inputs and the output. The following table shows the rules of the fuzzy controller, where all the entries in the matrix are the fuzzy sets of the error (E), the error variation (ΔE) and the cyclic ratio variation (ΔD) of the static converter [31]. The control rule must be designed so that the input variable (E) is always zero.

Table II.1 rules of fuzzy logic [31]

E \ ΔE	PP	EZ	NP	NG	PG
NG	PG	PG	EZ	EZ	PG
NP	PP	PP	EZ	EZ	PP
EZ	EZ	EZ	EZ	PP	EZ
PP	EZ	NP	NP	NP	EZ
PG	EZ	NG	NG	NG	EZ

II.6.4.3 Defuzzification

Finally, we must carry out the inverse operation of fuzzification, here we must calculate a numerical value understandable by the external environment from a fuzzy definition is this is the purpose of defuzzification. Defuzzification can be achieved using the center of gravity method mentioned above [31].

II.6.5 Advantages and Limitations of Fuzzy MPPT

Advantages:

- Robustness against sudden irradiance and temperature changes
- Does not require an accurate mathematical model of the PV array
- Better dynamic performance and fewer oscillations near the MPP.

Limitations:

- Requires careful design of the rule base and membership functions
- Performance may degrade if the inputs are not normalized or fuzzified correctly
- Computational complexity is higher than in simpler algorithms like P&O.

II.7 Conclusion

This chapter has provided a comprehensive overview of Maximum Power Point Tracking (MPPT) as a fundamental technique for enhancing the efficiency of photovoltaic energy systems. The basic principles and operational mechanisms of MPPT were thoroughly explained. Various conventional and advanced MPPT algorithms were examined, emphasizing their advantages and limitations. The comparative analysis of these techniques highlights the trade-offs between complexity, cost, and tracking accuracy. It is evident that optimizing the performance of solar power conversion systems heavily relies on the effectiveness of MPPT techniques. Therefore, continuous research and development in this field are essential to maximize energy extraction from renewable sources and to contribute significantly to sustainable energy production.

Chapter III Simulation Results and Discussion

III.1 Introduction

The last chapter discuss the obtained simulation results concerning the functioning of the studied PV system in both non-MPPT and MPPT modes. Firstly, the DC-DC converter is controlled by employing P&O MPPT algorithm to deliver the maximum energy extracted into the electrical grid via the PWM inverter. Then, the PV generator active power is injected into the network through the control of PWM DC-AC converter and according to the energy demanded by the grid manager using fuzzy logic controller. Finally, the effectiveness and the robustness of the studied control is well tested under different meteorological conditions.

III.2 Description of the studied PV system

In this section, the control of the PV system under analysis is based on the classical Perturb and Observe (P&O) algorithm. The synoptic scheme of the studied PV system is shown in Figure III.1 It is composed of a PV generator, a DC-DC boost converter, and a voltage source inverter (VSI) connected to the electrical grid. The MPPT technique is employed to extract the maximum available power from the PV array under varying environmental conditions. Moreover, the PWM inverter ensures the active power injection, synchronized power into the utility grid by converting the DC output of the boost converter into a balanced three-phase AC waveform.

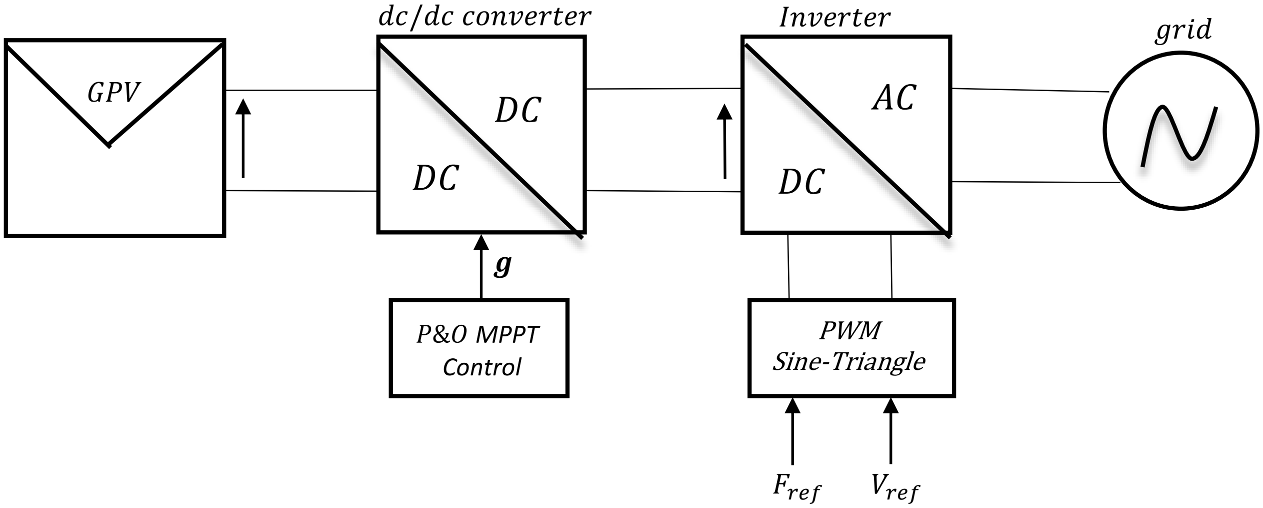


Figure III-1 Synoptic scheme of the studied PV system

III.2.1 Role of each component in grid connected PV system

- **GPV (Photovoltaic Generator)**

- This is the solar panel or array that converts solar irradiance into direct current (DC) electricity.

- It is the primary energy source in the system, and its output varies with sunlight (irradiance) and temperature.

- **DC/DC Converter**
  - The DC output from the PV generator is passed to a DC/DC converter (typically a boost converter).
  - Its role is to regulate the PV voltage and current to ensure the panel operates at its Maximum Power Point (MPP).
  - This operation is managed by the P&O MPPT Control (Perturb & Observe Maximum Power Point Tracking) block.
- **P&O MPPT Control**
  - This controller continuously adjusts the duty cycle of the DC/DC converter to find and maintain operation at the maximum power point of the PV module.
  - It does so by perturbing the voltage and observing the power response.
- **Inverter (DC/AC Converter)**
  - Converts the regulated DC output from the DC/DC converter into alternating current (AC), suitable for feeding into the electrical grid.
  - The inverter must synchronize its output with the grid's frequency and phase.
- **PWM Sine-Triangle (Modulation Block)**
  - This represents the sinusoidal pulse-width modulation (SPWM) strategy used to control the inverter.
  - It compares a sinusoidal reference voltage signal with a high-frequency triangular carrier signal to generate switching signals.
  - The output ensures that the inverter produces sinusoidal AC voltages that match the grid in frequency and phase.
- **Grid**
  - The final output from the inverter is injected into the electric power grid, allowing the PV system to supply renewable energy directly to the network.

III.3 PV system modelling

The equivalent single-phase circuit is illustrated by the corresponding Fresnel diagram (see Figure III-2). The parameters (R and X) denote the resistance and reactance of the line, and the diagram is plotted for an active backward power factor (PV system provides reactive power).

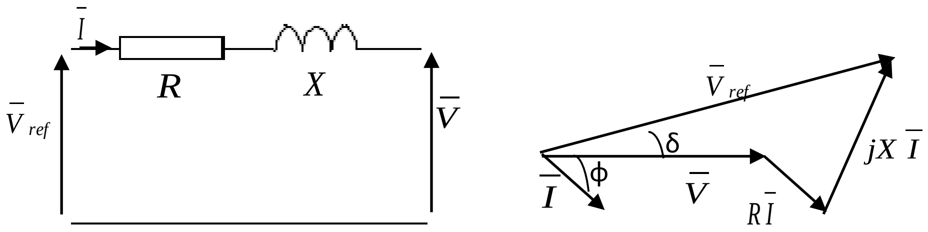


Figure III-2 Inverter + Network equivalent circuit and its Fresnel diagram

The reference voltage for controlling the inverter will therefore be given for a current I ensuring the injection of an apparent power $S = V.I$ into the grid by the following expression:

$$\bar{V}_{ref} = \bar{V} + R\bar{I} + jX\,\bar{I} \qquad \text{(III.1)}$$

This expression allows us to establish the amplitude of the reference voltage and its phase shift relative to the network voltage.

Also, the grid busbar voltages and the inverter voltages are given by the following equations respectively:

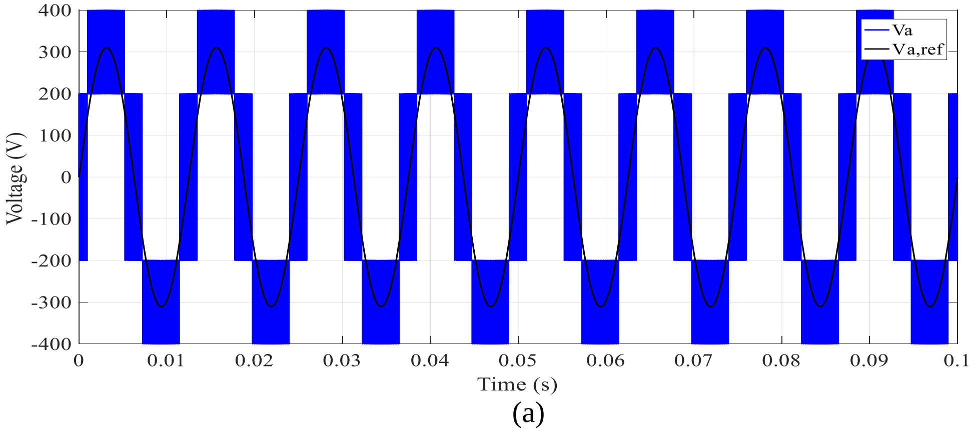
$$\begin{cases} V_{ja} = 380\sqrt{\frac{2}{3}}\cos(\omega t) \\ V_{ja} = 380\sqrt{\frac{2}{3}}\,cos(\omega t - \frac{2\pi}{3}) \\ V_{ja} = 380\sqrt{\frac{2}{3}}\,cos(\omega t + \frac{2\pi}{3}) \end{cases} \qquad \text{(III.2)}$$

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \frac{E}{6} \begin{bmatrix} +2-1-1 \\ -1+2-1 \\ -1-1+2 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad \text{(III.3)}$$

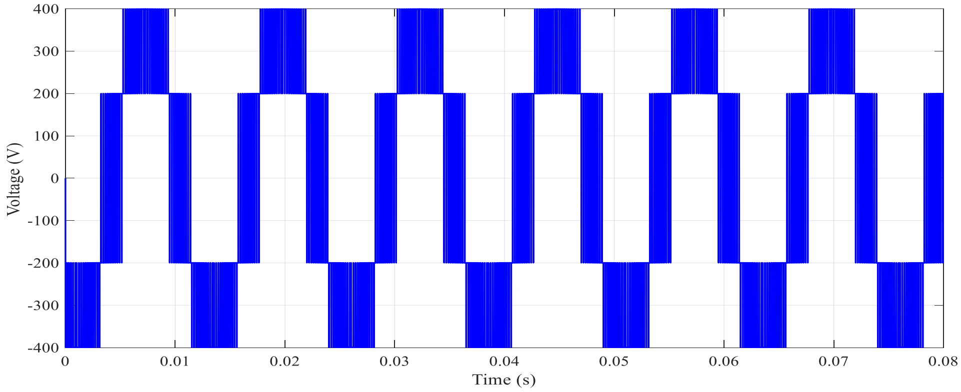
III.3.1 Simulation results based on classical P&O algorithm

The PV system under analysis consists of a 30 kW PV array, a DC-DC converter and a three-phase PWM inverter (f_{ref}=50 Hz and V_{ref}=220V). A calculation step size is chosen to be h=10^{-}5 s, a carrier frequency of around 53 times the frequency used, i.e., 3.18 kHz and a V_{dc} bus voltage of 600 V.

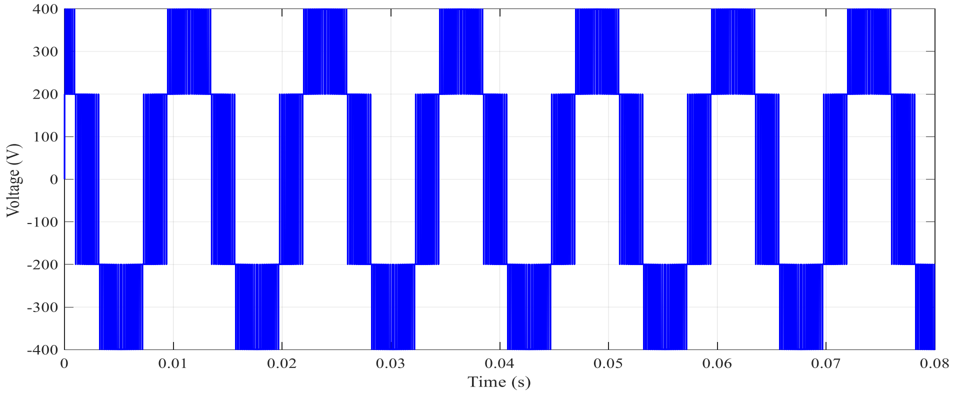
In this simulation, the sinusoidal pulse width modulation (PWM) technique is used to control the voltage source inverter by producing the gating signals for the semiconductor switches. This technique is used to obtain three phase output voltages that can be controlled in magnitude and frequency. In fact, the waveforms of the voltages V_{abc} (t) at the output of the inverter are shown in Figure III.3, where PV arrays are operating under standard condition: irradiation = 1000/m ^{2} and temperature = 25°C.



(a)



(b)



(c)

Figure III-3 Voltages waveforms at the output PWM inverter

One can observe from Figure III.3 (a) that the simple voltage V_a alternates between 2 $V_{dc}/3$, $V_{dc}/3$ on the one hand, and $-V_{dc}/3$, -2 $V_{dc}/3$ on the other hand. It is clear that the output voltages need to be filtered to obtain clean sinusoidal voltages. The harmonic content in the output voltages of the inverter depends on the choice of the switching frequency.

Moreover, the triangle carrier wave V_{tri1}, is used in the producing PWM signal (see Figure III.4. This high-frequency signal (typically at a multiple of the grid frequency) are compared against to the sinusoidal reference voltage to generate the switching signals for each inverter leg.

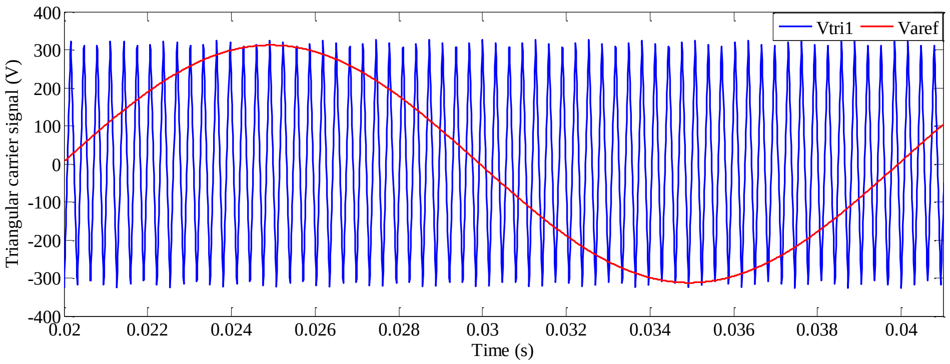


Figure III-4 Triangle-sine PWM

Also, the grid busbar voltages are presented in the Figure III.5. They take a sinusoidal waveform and have a constant amplitude and stable frequency (50Hz). The inverter aims to match these grid voltages in both amplitude and phase through its control algorithms, particularly to ensure a unity power factor operation as indicated by cos ϕ=1.

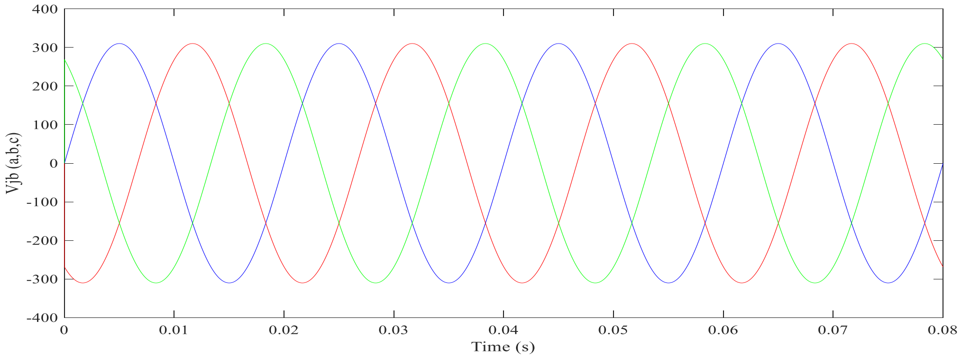


Figure III-5 Grid busbar voltages waveforms

In addition, figure III 6 represent the currents i_a,i_b and i_c (t) injected into the grid by the inverter. They are non-sinusoidal due to the harmonics generated by the PWM inverter. To solve this problem and to improve the grid power quality, a passive filter as LC or LCL filter is usually placed between the VSI and the electrical grid. Note that the THD limited by the IEEE std 519-2014 is indeed about 5%.

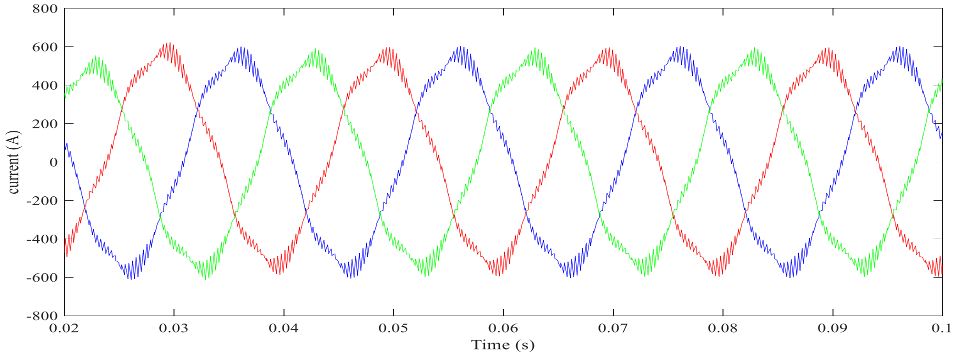


Figure III-6 Grid currents iabc (A)

III.4 Control of the PV System in non-MPPT and MPPT modes using fuzzy logic technique

Two fuzzy controllers are used to generate the reference currents in *dq* reference that will be used to calculate the reference current of the three phases (*abc*) necessary for controlling the three arms of the three -phase PWM inverter with hysteresis current technique (see Figure III 7).

The first one is employed for controlling the active power and the second controller is used to adjust the reactive power of the PV field.

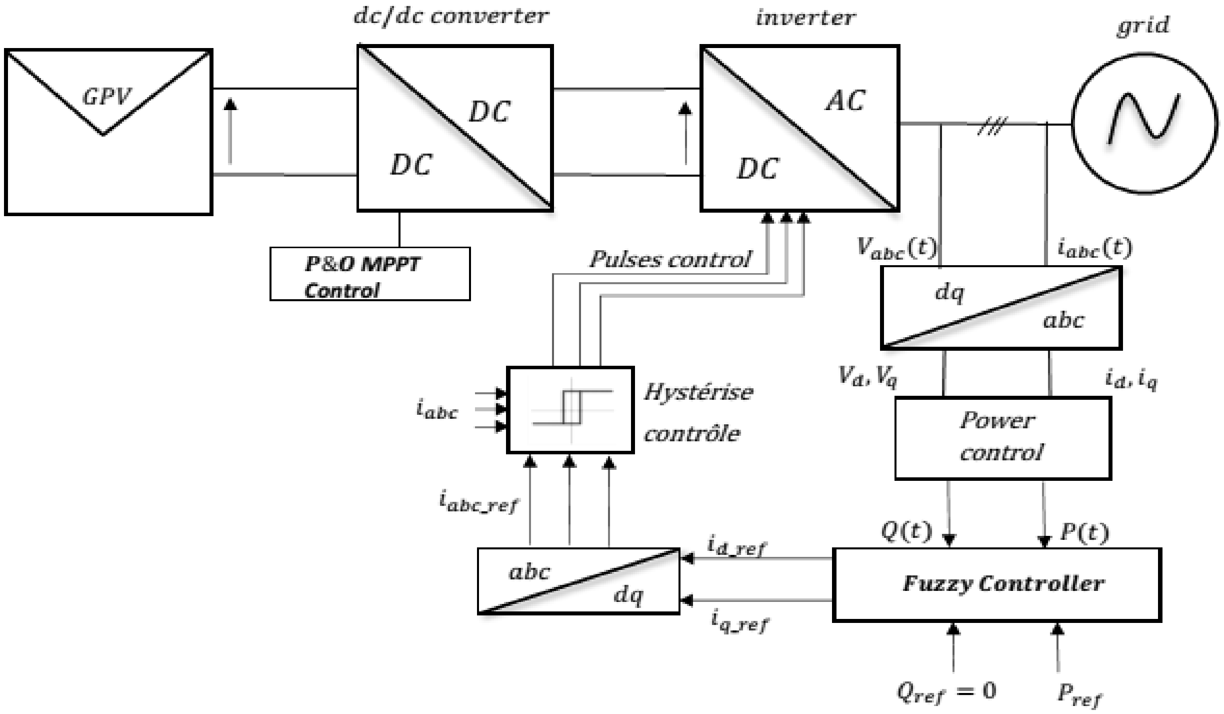


Figure III-7 Control of PV system through fuzzy logic controller

III.5 Fuzzy controllers modelling of active and reactive powers

The Park transformation is used to express the grid tensions in the frame (*d*, *q*). We can then write:

$$\begin{cases} V_d = \frac{2}{3}\left(V_{ja}(t)\cos(\omega t) + V_{jb}(t)\cos(\omega t - \frac{2\pi}{3}) + V_{jc}(t)\cos(\omega t + \frac{2\pi}{3}) \right) \\ V_q = -\frac{2}{3}\left(V_{ja}(t)\sin(\omega t) + V_{jb}(t)\sin(\omega t - \frac{2\pi}{3}) + V_{jc}(t)\sin(\omega t + \frac{2\pi}{3}) \right) \end{cases} \quad \text{(III.4)}$$

Thus, the PV field powers can be injected into the grid are expressed by [29]:

$$\begin{cases} P = \frac{3}{2}(V_d i_d + V_q i_q) \\ Q = \frac{3}{2}(V_d i_q - V_q i_d) \end{cases} \quad \text{(III.5)}$$

The inputs of the first fuzzy controller are the real power error e_P and the variation Δ_{eP}, are given by the following expression [31], [32]:

$$e_P = P_{ref} - P \quad \text{(III.6)}$$

$$\Delta e_p = (1 - z^{-1}) e_p \quad \text{(III.7)}$$

Also, the reactive power control is achieved by using a second fuzzy logic controller. Its inputs are expressed by:

$$e_Q = Q_{ref} - Q \quad \text{(III.8)}$$

$$\Delta e_Q = (1 - z^{-1}) e_Q \quad \text{(III.9)}$$

As a result, the figure shown below illustrates the structure of two fuzzy logic controllers used for controlling the 30 kW PV array power.

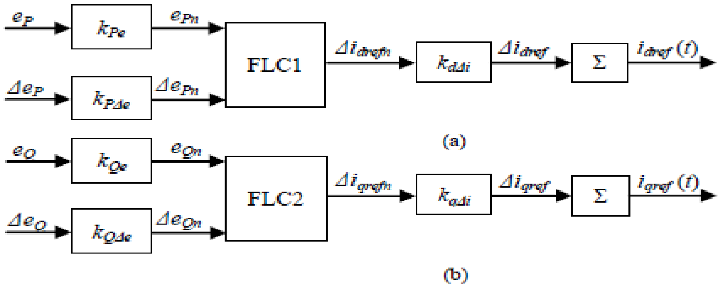
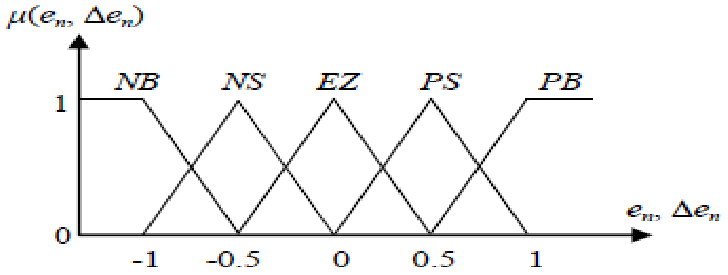
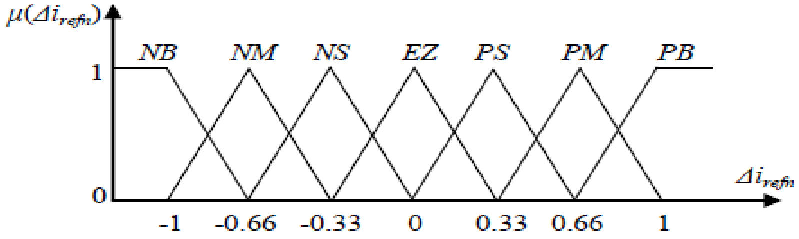


Figure III-8 Structure of Fuzzy logic controllers

where, k_{Pe}, $k_{P\Delta e}$ and $k_{d\Delta i}$ are the normalization gains. For the fuzzification, the membership functions of e_n, Δe_n and Δ_{idrefn} are presented in Figure III 9.



a) Input membership functions



b) Output membership functions

Figure III-9 Fuzzification of the inputs/outputs of FLC1 and FLC2

Table III. 1 Inference matrix of FLC1 and FLC2

e_n Δe_n	***NB***	***NS***	***EZ***	***PS***	***PB***
NB	*NB*	*NB*	*NM*	*NS*	*EZ*
NS	*NB*	*NM*	*NS*	*EZ*	*PS*
EZ	*NM*	*NS*	*EZ*	*PS*	*PM*
PS	*NS*	*EZ*	*PS*	*PM*	*PB*
PB	*EZ*	*PS*	*PM*	*PB*	*PB*

III.6 Role of each component in grid connected PV system

- **Photovoltaic Generator (GPV)**

The PV generator converts solar energy into direct current (DC) electricity. It serves as the main energy source for the system, producing variable voltage and current depending on solar irradiance and temperature.

- **DC/DC Converter with MPPT Control (P&O Algorithm)**

A DC/DC converter (typically a boost converter) regulates the voltage from the PV panel to optimize power transfer. It is governed by the Perturb and Observe (P&O) MPPT algorithm, which adjusts the duty cycle to track the Maximum Power Point (MPP) of the PV array in real time.

- **DC/AC Inverter**

The inverter converts the regulated DC voltage into AC voltage suitable for grid injection. It ensures synchronization in frequency, voltage, and phase with the utility grid.

- **Voltage and Current Measurement**

Three-phase voltages and currents at the inverter output are measured to enable closed-loop control. These signals are essential for transforming into the rotating reference frame (dq) and for power computation.

- **$\mathbf{abc} \rightarrow \mathbf{d_q}$ Transformation (Park Transformation)**

This block transforms the measured three-phase quantities from the stationary reference frame (abc) to the rotating dq reference frame. This simplifies control by decoupling active and reactive power components.

- **Power Control Block**

The power controller calculates the **active power (P)** and **reactive power (Q)** from the dq components of voltage and current. These calculated values are compared to their reference values and sent to the fuzzy controller.

- **Fuzzy Logic Controller**

The fuzzy controller receives the actual power values $P(t), Q(t)$ and their references P_{ref}, Q_{ref}. it generates reference currents in the dq frame: i_{d_ref}, i_{q_ref} , based on fuzzy logic inference rules. These references aim to maintain the desired power exchange with the grid.

Typically, $Q_{ref} = 0$ to enforce unity power factor operation.

- **$\mathbf{dq} \rightarrow \mathbf{abc}$ Transformation (Inverse Park)**

This block converts the current references from the dq frame back into the abc frame, making them suitable for comparison with measured currents in hysteresis current control.

- **Hysteresis Current Controller**

The hysteresis controller compares the actual current i_{abc} with the reference current i_{abc_ref} and generates switching signals (gate pulses) for the inverter switches.

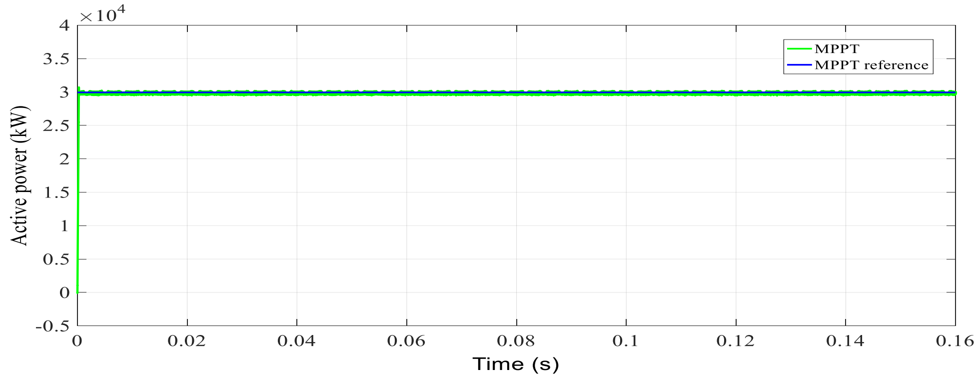
- **Grid Connection**

Finally, the properly regulated and synchronized AC current is injected into the utility grid. The system operates efficiently and meets grid requirements in terms of power quality, frequency, and voltage levels.

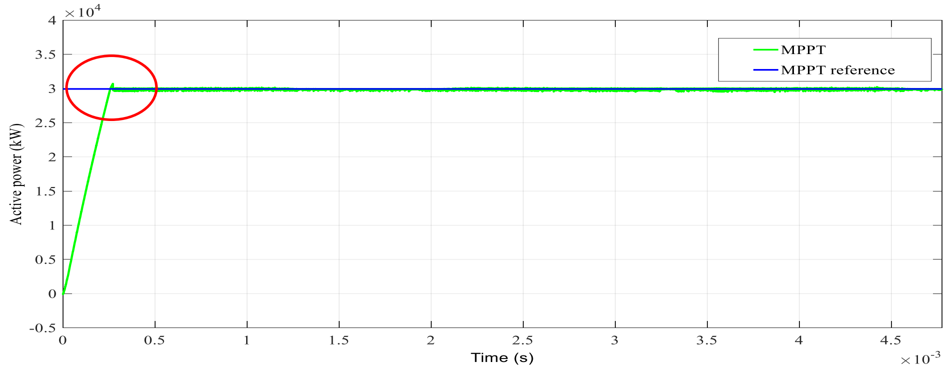
III.7 Simulation results using fuzzy logic controllers

III.7.1 Control of PV system with fuzzy logic MPPT

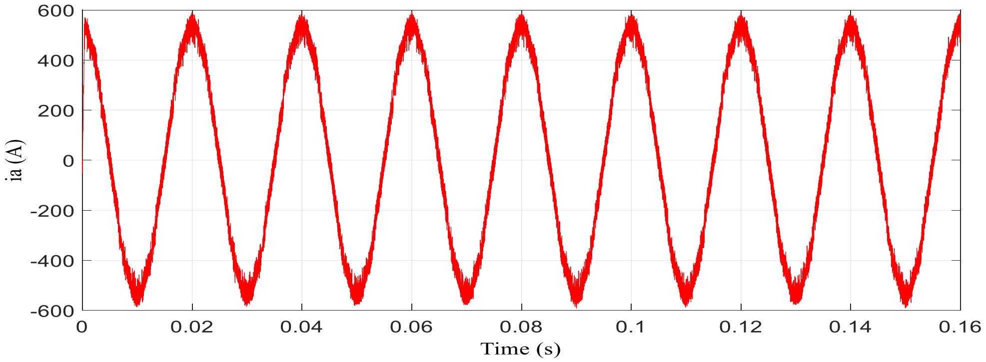
In order to extract the maximum power converted by the PV generator (MPPT), a simulation is performed for standard conditions (a temperature of 25 ° C and an irradiation of 1000 W / m²). The active power reference is equals to the maximum power converted losses of the line is near 29,938 kW while the reactive power reference is fixed at zero. Figure III- 10 (b) shows that the maximum power point is quickly reached after 0.025s sec. Moreover, figure III- 10 (c and d) show respectively the grid current and the inverter output voltage waveform.



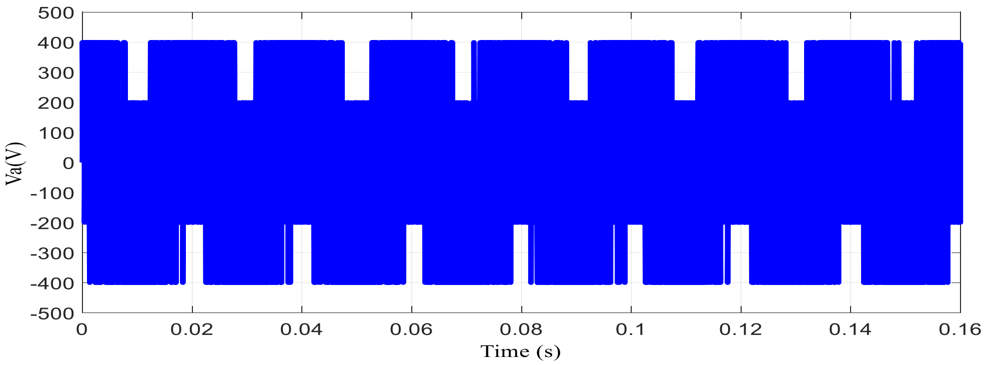
(a)



(b)



(c)

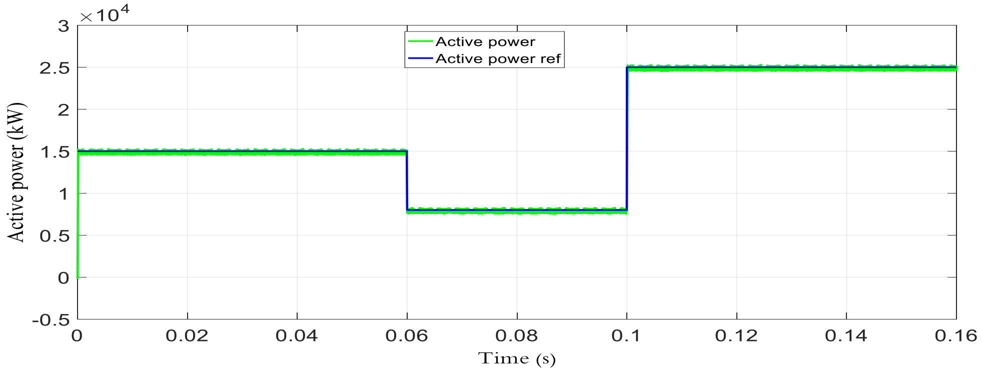


(d)

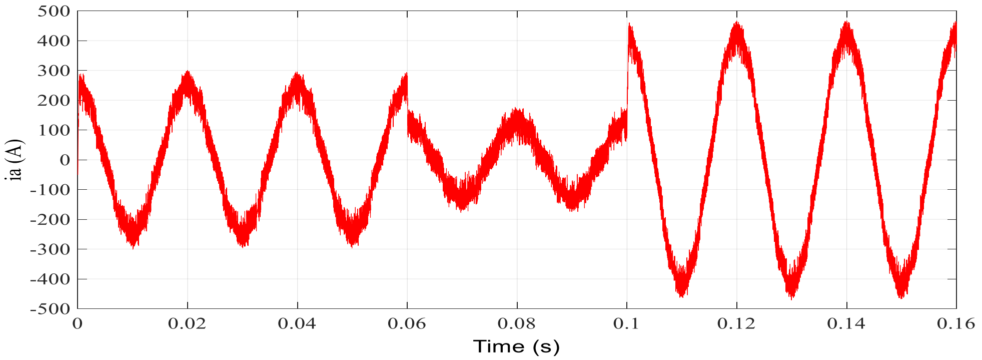
Figure III-10 MPPT power production under G= 1000 W / m² and a T =25 ° C: a) Active power injected into the grid, b) Zoom of active power, c) Grid current, d) Inverter output voltage

III.7.2 Control of PV system in non-MPPT mode

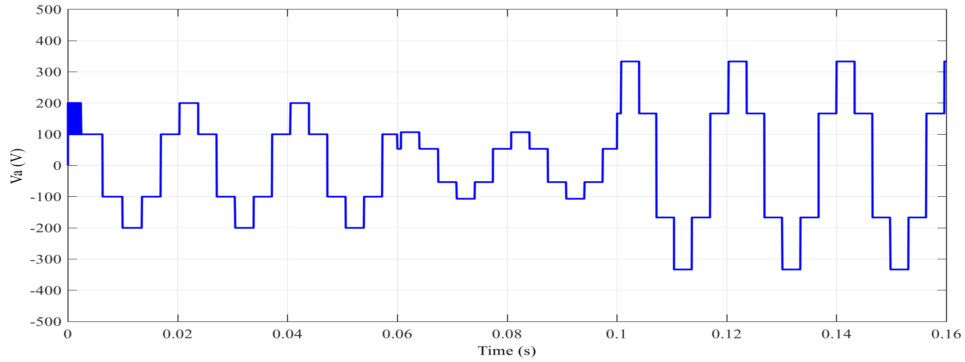
In this case, the active power injected to the grid is a purely active power. Figure III 11 (a) shows the responses of PV powers for a change in its reference. As can be seen from the waveforms, the real power is varied according to its reference power during different phases under standards parameters of temperature and irradiance. Also, the current and the voltage of the first phase of inverter are shown in figure III 11 (b, c). The obtained results show that current amplitude changes depending on the required active power, under a substantially unity power factor.



(a)



(b)



(c)

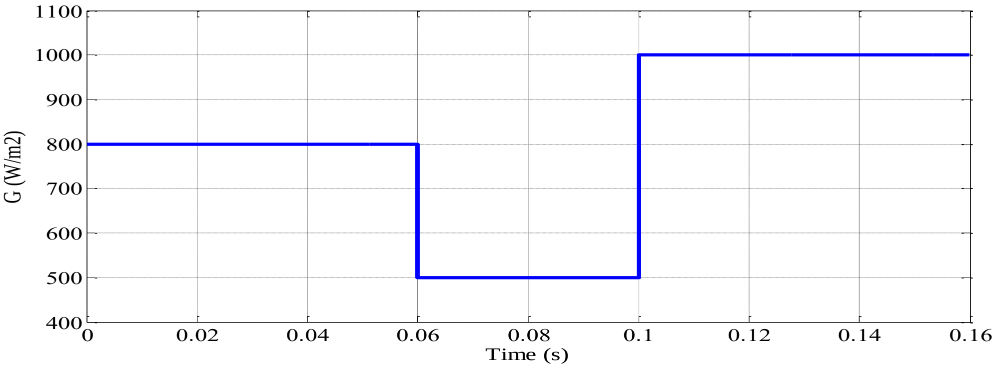
Figure III-11 Real power injection under an irradiance of 1000 W/ m² and a temperature of 25 ° C: a) Active power injected into the grid, b) Grid current, c) Inverter output voltage

III.7.3 Robustness of fuzzy logic MPPT control

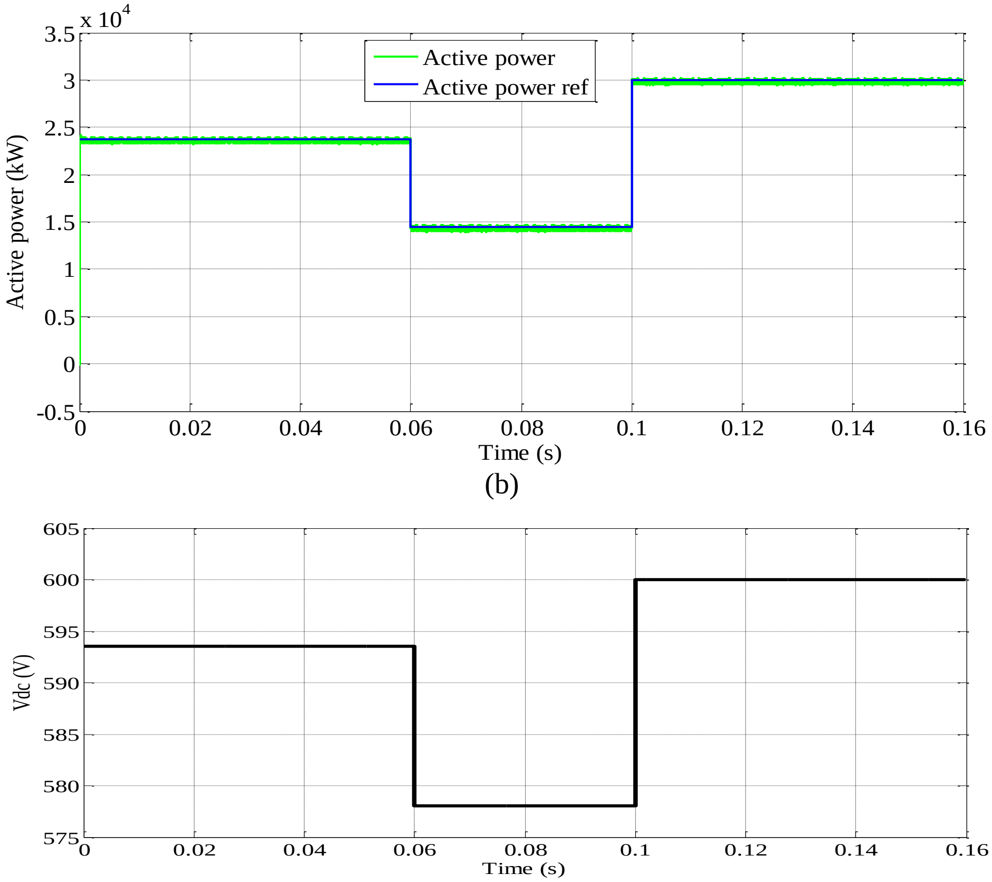
One of the most important aspects of an MPPT control strategy is its robustness and its ability to maintain optimal performance despite sudden or significant environmental changes. Fuzzy logic-based MPPT controllers are known for their flexibility and adaptability, making them suitable for real-time tracking of the maximum power point under dynamic operating conditions. This section evaluates the robustness of the proposed fuzzy logic MPPT algorithm under two main scenarios of variation: changes in solar irradiation and fluctuations in temperature.

a) Under irradiation variations

In this first case, the performance of the fuzzy logic MPPT controller is tested under varying solar irradiance levels. In this simulation, we will set the temperature at 25°C and vary the irradiation as a function of time (see Figure III 12 (a)). From figure III 12 (b), it is clear that the variation in irradiation results in a change in the active power setpoint and consequently the maximum power point changed from 23,717 kW (for an illuminance of 800 W/m²) to 14,431 kW (corresponding to an irradiation of 500 W/m²) and then to 29,938 kW (for G= 1000 W/m²).



(a)



(b)

(c)

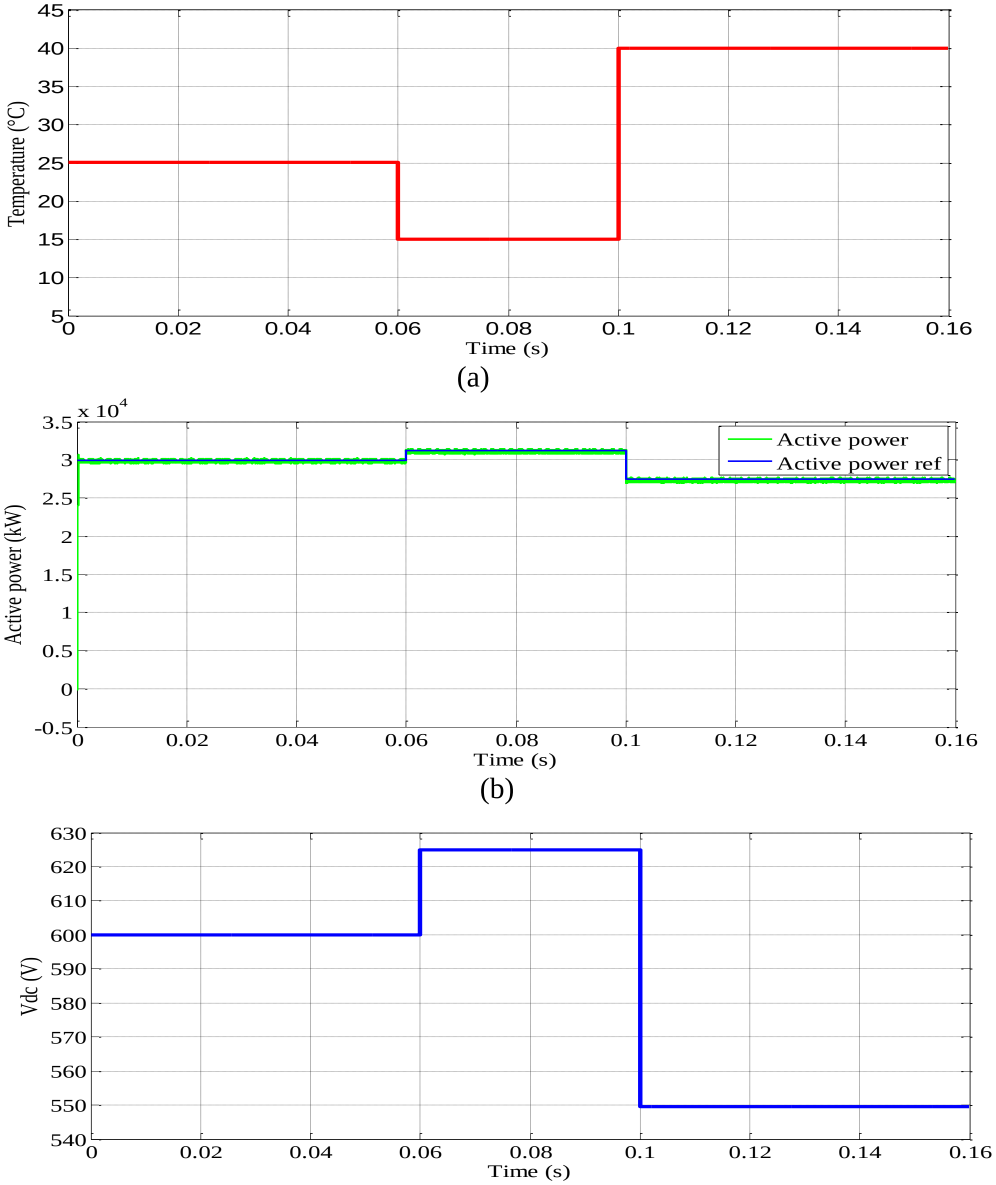
Figure III-12 Performance of fuzzy logic MPPT control under irradiation variations: a) Solar Irradiance Profile, b) Active power Tracking c), DC bus voltage response

In addition, the DC bus voltage varied depending of the active power level injected into the grid, as can be seen in figure III 12 (c). On can note that the fuzzy control responds to bring the power back to its setpoint quickly and appropriately.

b) Under temperature variation

Temperature is an important factor influencing the static *I-V* characteristic of the PV generator and, consequently, its power. We will perform the same test as before. We set the irradiation at 1000 W/m² and gradually vary the temperature from 25°C to 15°C at t=0.06 s and then from 15°C to 40°C at t=0.1 s (see figure III 13 (a)). It shows clearly that a decrease in temperature from 25°C to 15°C increases the active power setpoint from 29.93 kW to 31,18 kW. While decreasing the temperature from 15°C to 40°C decreases the maximum available power to 27.40 kW, as shown in figure III 13 (b). Consequently, the DC bus voltage follows its reference power, see figure III 13 (c).

In summary, we note that the fuzzy control of the active power remains decoupled and insensitive to this temperature variation.



(c)

Figure III-13 Performance of fuzzy logic MPPT control under temperature variation: a) Temperature Profile, b) Active power Tracking c), DC bus voltage response

III.8 Conclusion

This chapter describes the structure and steps constituting the algorithm of a fuzzy controller, and its application to the control of active power injected into the grid by a PV array via a PWM inverter for both non-MPPT and MPPT operational modes. At the first, a simulation concerning the PV system functioning with P&O MPPT algorithm has been performed.

Moreover, to ensure a control of the studied PV system with and without MPPT, fuzzy logic technique was successfully applied. Finally, the robustness of the proposed control has been tested under different meteorological parameters of irradiation and temperature.

General Conclusion

In this thesis, we have addressed the issue of improving the performance of grid-connected photovoltaic (PV) systems through the integration of Artificial Intelligence (AI) techniques, with a specific focus on Maximum Power Point Tracking (MPPT) and system control optimization.

Chapter I provided a general overview of photovoltaic systems, emphasizing the fundamental principles of solar energy conversion, the architecture of PV systems, and their integration with the electrical grid. We highlighted the challenges that hinder the efficiency of PV energy conversion, such as environmental variability and system non-linearity.

In chapter II, we explored various MPPT techniques, focusing on their role in maximizing the energy extracted from PV panels under dynamic operating conditions. We analyzed both conventional methods and intelligent algorithms, underlining the advantages of AI-based approaches, particularly fuzzy logic controllers, in handling uncertainties and improving tracking precision.

In the last chapter, a simulation and analysis using MATLAB/Simulink of the proposed artificial control strategy have been presented. The obtained simulation results demonstrated that the classical P&O algorithm can be used to control the grid connected PV system with MPPT operational mode. While, the functioning of the studied PV system in non-MPPT mode is achieved through the application of the fuzzy logic technique. Finally, to validate the suggested control, its performance is tested in terms of robustness during standard and variation of climatic parameters of irradiation and temperature.

As perspectives for this work, we will also propose to study the control of the grid connected PV systems functioning with and without MPPT algorithm using other modern control techniques such as those of artificial intelligence (neural networks and neuro-fuzzy systems). It would also be very interesting to implement its control procedures (the practical realization).

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