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Improved Control of PV System using Variable Step Size

Defended in front of the jury composed of:

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Dedication

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I dedicate this work with deep gratitude and sincere words to:

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Résumé

Dans le contexte actuel, où le développement industriel, économique et écologique est une priorité, l'énergie photovoltaïque représente une option favorable par rapport à l'utilisation de combustibles fossiles, qui sont connus pour être nocifs pour l'environnement. Cette étude présente une méthode améliorée de suivi du point de puissance maximale pour les systèmes photovoltaïques basés sur un convertisseur DC-DC Boost, en utilisant une méthode de taille de pas variable, comparée aux inconvénients de la méthode algorithmique MPPT conventionnelle. De ce fait Cinq méthodes MPPT ont donc été analysées et comparées : la première est la méthode Perturbation et Observation avec un pas fixe, la deuxième est la méthode P&O avec un pas variable, la troisième est la méthode IC (Conductance incrémentale) avec un pas fixe, la quatrième est la méthode IC avec un pas variable, et la cinquième est le contrôleur PID (Proportionnelle Intégrale et dérivée). Cette étude a été réalisée à l'aide d'un panneau solaire de 100 kW dans des conditions de température fixe et d'irradiation solaire variable dans Matlab/Simulink. Les résultats montrent l'efficacité de la taille de pas variable en termes de temps de réponse rapide, de dépassement et de suivi précis du MPP.

Mots clés :

Système photovoltaïque, convertisseur Boost, suivi du point de puissance maximale, perturbation et observation, conductance incrémentale, dérivée proportionnelle intégrale, taille de pas fixe, taille de pas variable.

Abstract

In the present context, where industrial, economic, and ecological development are the priorities, photovoltaic energy stands as a favorable option when compared to the use of fossil fuels, which are known to be harmful to the environment. This study presents an improved Maximum Power Point Tracking (MPPT) method for photovoltaic systems based on a DC-DC boost converter, using a variable step size method, compared to the drawbacks of the conventional algorithmic MPPT method. Therefore, five MPPT methods were analyzed and compared: the first is the Perturb and Observe method with fixed step size, the second is the P&O method with variable step size, the third is the IC (Incremental Conductance) method with fixed step size, the fourth is the IC method with variable step size and the fifth is the PID (Proportional Integral and Derivative) controller. This study was carried out using a 100kW solar panel under fixed temperature and variable irradiation conditions in MATLAB/Simulink. The results show the effectiveness of variable step size in terms of fast response time, overshoot and accurate tracking of MPP.

Keywords:

Photovoltaic system, Boost converter, Maximum Power Point Tracking, Perturbation and Observation, Incremental Conductance, Proportional Integral Derivative, Fixed Step Size, Variable Step Size.

ملخص

في السياق الحالي، حيث تعتبر التنمية الصناعية والاقتصادية والبيئية من الأولويات، تعتبر الطاقة الكهروضوئية خياراً مفضلاً مقارنةً باستخدام الوقود الأحفوري المعروف بضرره على البيئة. تقدم هذه الدراسة طريقة محسّنة لتتبع نقطة الطاقة القصوى للأنظمة الكهروضوئية القائمة على محول معزز للتيار المستمر-التناوب المستمر باستخدام طريقة متغيرة حجم الخطوة، مقارنةً بعيوب الطريقة الخوارزمية التقليدية MPPT. ولذلك تم تحليل ومقارنة خمس طرق MPPT: الأولى هي طريقة الاضطراب والملاحظة مع حجم خطوة ثابت، والثانية هي طريقة P&O مع حجم خطوة متغير، والثالثة هي طريقة IC (التوصيل التزايدي) مع حجم خطوة ثابت، والرابعة هي طريقة IC مع حجم خطوة متغير، والخامسة هي طريقة PID (المتحكم التناسبي التكاملي والاشتقاقي). أُجريت هذه الدراسة باستخدام لوحة شمسية بقدرة 100 كيلوواط في ظل درجة حرارة ثابتة وظروف إشعاع شمسي متغيرة في MATLAB/Simulink. تُظهر النتائج فعالية حجم الخطوة المتغير من حيث سرعة الاستجابة والتجاوز والتتبع الدقيق ل MPP.

الكلمات المفتاحية:

النظام الكهروضوئي، محول التعزيز، تتبع نقطة الطاقة القصوى، الاضطراب والملاحظة، التوصيل التزايدي، المشتق التناسبي التكاملي، حجم الخطوة الثابتة، حجم الخطوة المتغيرة.

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Abbreviations

A: Ampere

ANOVA: Analysis of Variances

C: Coulomb

D: Duty cycle

DC/DC: Continuous-Continuous

GPV: Photovoltaic Generator

I: Current

IC: Incremental Conductance

IGBT: Insulated-Gate Bipolar Transistor

I-V: Current-Voltage

J: Joule

K: Kelvin

kp: Proportional gain

ki: Integral gain

kd: Derivative gain

kW: Kilowatt

MOSFET: Metal-Oxide Semiconductor Field-Effect Transistor

MPPT: Maximum Power Point Tracker

MPP: Maximum Power Point

P: Power

PV: Photovoltaic

P-V: Power-Voltage

Pmax: Maximum Power

P&O: Perturb & Observe Algorithm

PID: Proportional-Integral-Derivative

SPV: Photovoltaic Solar

V: Voltage

W: Watt

GENERAL INTRODUCTION

General Introduction

Electricity has become one of the most important aspects of human life. Non-renewable and renewable energy sources can be used to produce electrical energy.

Since the widespread use of electricity, energy consumption has been risen steadily. tripled from the 1960s to the present day. Today, the main sources of energy are fossil fuels (coal, oil, natural gas). However, since the oil crises that followed the 70s, the problem of energy conversion and storage of energy has led to research and development of new sources of supply. This interest has grown in the face of the inevitable depletion of fossil fuels impact on the environment and the waste they generate[1]. The growing demand for electrical energy, particularly in isolated locations without dependable electricity, including deserts and hilly regions, is propelling a notable increase in the use of renewable energies globally[2].

The most researched electric power sources are renewable energy sources, such as solar cells and wind turbines, which are the most extensively used renewable energy sources. Due to its lack of moving parts and lower environmental pollutants, the photovoltaic model has gained a lot of attention in recent decades[3].

Photovoltaic solar energy has the advantage of converting the Sun's energy directly into electricity. Applications began in the early 1960s, in satellites and consumer products such as watches and calculators. It's a decentralized form of energy, ideal for producing electricity in isolated locations, where it avoids the need to invest in kilometers of power lines to connect to the grid. Some scenarios predict that photovoltaics could become one of the world's top two energy sources within 40 or 50 years[4]. The challenge of current research is to improve the efficiency and reduce the cost of photovoltaic cells.

The work carried out in this study revolves around the use of solar energy obtained via a photovoltaic generator (GPV) to ensure optimum extraction of this energy, a boost-type DC/DC converter is used for the adaptation. The control technique adopted is maximum power operating point tracking (MPPT) corresponding to optimum PV panel voltage and current, for which power is maximized whatever the metrological conditions (irradiation, temperature...). Different techniques of MPPT will be used and a comparison between them for an optimal result.

We structured the work into the following three chapters:

The **first chapter** covers the general points and theories that are essential for understanding photovoltaic solar energy in the production of electrical energy. It starts with an explanation of the photovoltaic effect and the principles of photovoltaic conversion. then the different types of photovoltaic cells, the connections of modules (series and parallel), the characteristic parameters of PV cell and its main advantages and disadvantages, are discussed. the second section of this chapter gives an overview of other categories of renewable energy, the advantages and disadvantages of this previous.

In the **second chapter**, the photovoltaic cell, its mathematical representation model, its characteristics and its direct dependence on irradiation and temperature are studied. The second section of this chapter presents different DC/DC converter topologies for power interface design, and their operating principles are explained. This is followed by a description of the different methods (MPPT) used in this study to find the maximum power point (MPP), and a brief comparison between them according to certain specifications.

The **last chapter** is dedicated to the simulation results of the studied system and its discussion. It begins with a brief introduction to the MATLAB environment, then the specifications and characteristics of the PV array used in this study, followed by the simulation results of the MPPT techniques separately, then a combination and comparison between them according to different cases.

At **the end** of our work there was a general conclusion.

CHAPTER I: PHOTOVOLTAIC SYSTEM AND OTHER CATEGORIES OF RENEWABLE ENERGY ON REVIEWS

Introduction

Renewable energy sources have immense potential because they can supply several times the present energy demand. They can lower local and global air emissions, provide long-term sustainable energy supplies, and increase market diversity for energy. [5]. Additionally, they can offer economically viable solutions to address specialized energy service demands (especially in rural and emerging nations), generate new job opportunities, and present prospects for equipment production locally.

Solar energy is the most encouraging and free source of energy and the most powerful of all renewable energies.

This chapter is dedicated to the introduction of photovoltaic systems, presenting the history, definition of photovoltaic energy and explaining the photovoltaic effect. The principle of photovoltaic conversion will be discussed, along with the types and characteristics of photovoltaic cells. we will also cover the different connections of modules. finally, we will conclude by highlighting the advantages and disadvantages of renewable energy.

I.1 Photovoltaic energy

I.1.1 Definition

Photovoltaic energy, which involves the conversion of sunlight into electricity, refers to the generation of electricity from solar radiation using solar cells or solar panels. Solar cells are made of semiconducting materials, typically silicon, that convert sunlight directly into electricity through the photovoltaic effect. Solar is considered to be a renewable and sustainable source of energy that can be used to power a variety of applications ranging from small devices to large-scale.

I.1.2 Historic

The photoelectric effect was discovered in the 19th century. In 1839, the French physicist Alexandre Edmond Becquerel [6].He observed that certain materials could produce a small current under the effect of light: this phenomenon enables the conversion of light into electricity. Later, many scientists contributed to the development of this discovery, including Charles Fritts, Edward Weston, Nikola Tesla and Albert Einstein. The latter was awarded the Nobel Prize in 1921 for his work on the "photoelectric effect", proving that light is not only a wave, but that its energy is carried by particles: photons[7, 8].

The development of the semiconductor industry in the late 50s of the 20th century led to the technological development of solar cells[9]. It wasn't until the 1970s that manufacturers began to invest in solar cell technology Photovoltaics. Efforts to reduce production costs led to the widespread use of photovoltaic energy. In 1973, the first house powered by photovoltaic cells was built by the University of Delaware[10].

Beginning in the 1980s, the photovoltaic industry made steady progress, culminating in the construction of multi-megawatt power plants[11].

I.1.3 The photovoltaic effect

The process by which a semiconductor device known as a solar cell transforms the sun's energy emitted in the form of photons into electrical energy is known as the photovoltaic effect. This process has three steps:

a- Sunlight photon absorption.

b-Conversion of the energy received from the photons into electrical energy.

c- Particle accumulation in an external electrical circuit.

I.1.4 The principle of photovoltaic conversion

The photovoltaic cell consists of a semiconductor material that plays a critical role in its operation.

Photons can either flow through, reflect off, or be absorbed by the semiconductor material when they interact with a photovoltaic cell. Only the absorbed photons provide the energy necessary to generate electricity. As the semiconductor material absorbs sunlight (solar energy), electrons are released from the atoms within the material. Special treatments are applied to the surface of the material during production to make the front surface of the cell more receptive to these dislodged electrons, allowing them to naturally migrate towards the internal electrical circuit of the cell.[12].

The photovoltaic cell functions as a generator, creating an electron circulation in the external circuit. Typically, the voltage produced by the cell ranges from 0.3 V to 0.7 V, depending on factors such as the factors such as the material used, its arrangement and the temperature of the cell.

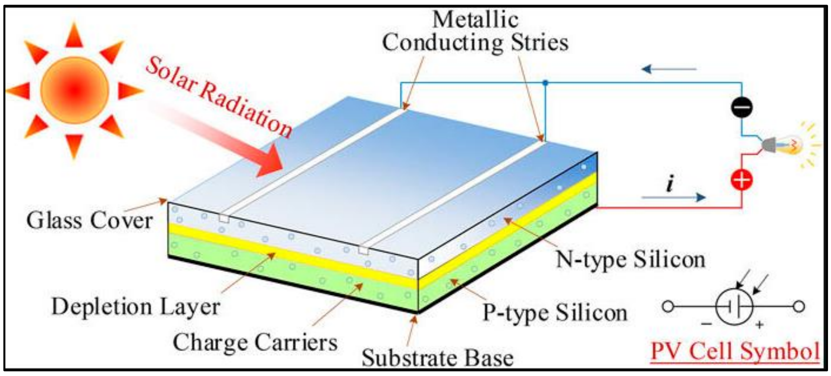

Figure I.1 Structure of a photovoltaic cell [13].

Solar radiation is made up of photons, each of which carries an energy Eph, which is given by the following equation:

$$E_{ph} = h\frac{c}{\lambda} \tag{I.1}$$

h: the Planck constant (h = 6,62x 10-34 J.S).

c: celerity of light in meters per second (3.108 m. s-1).

λ: wavelength in meters (m)

I.1.5 The type of photovoltaic cells

The cell is the best conversion unit for the photovoltaic effect. The amount of energy recovered depends on the materials and design of the cells. As a result, many solutions have been developed, which will be briefly presented in the following subsections.

a) Monocrystalline cells

This is the first generation of solar cells, and comes closest to the theoretical model. These cells are actually made up of numerous pure silicon crystals specially produced for the purpose, each around 10cm in size. These crystals are then sawn into ultra-thin plates, doped and connected[13].

These cells achieve high efficiencies of between 12% and 18%, and up to 24.7% in the laboratory. However, they have a number of disadvantages:

- Difficult and therefore very expensive production method (complicated manufacturing).
- A great deal of energy is required to obtain a pure crystal.

Figure I.2 Monocristalline photovoltaic cell.

b) Polycrystalline cells

Polycrystalline cells are made up of a collection They are characterized by:

- Lower production costs.
- Requires 2 to 3 times less energy to manufacture.
- 13% efficiency and up to 20% in the lab.

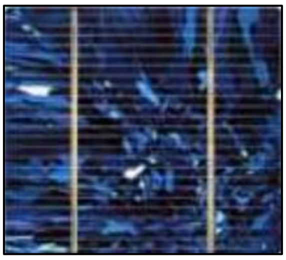

Figure I.3 Polycristalline photovoltaic cell.

c) Amorphous cells

Amorphous silicon appeared in 1976. Its atomic structure is disordered and not crystalline.

The use of amorphous silicon for solar cells has shown significant advantages in terms of both electrical properties and the manufacturing process. It offers a simple manufacturing process, low energy consumption, cost effectiveness and the ability to produce large area cells. However, despite the production costs, amorphous silicon solar cells have two disadvantages. Firstly, they have lower conversion efficiency than monocrystalline and polycrystalline silicon cells. Secondly, their power output drops rapidly by 10% to 20% during the first three to six months of operation[13].

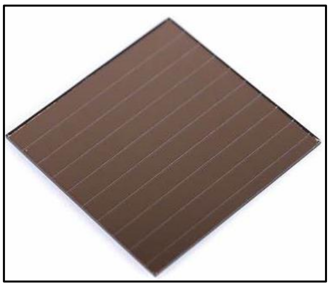

Figure I. 4 Amorphous photovoltaic cell.

I.1.6 From Module to photovoltaic Array

The PV module is therefore made up of several cells linked in series and/or parallel, arranged in rows. This assembly of cells differs from one technology to another and can lead to losses in addition to those mentioned above within the cell (optical and electrical losses)[14]. The modules are connected in series or in parallel to form a solar array. Together, these panels form a PV system or array.

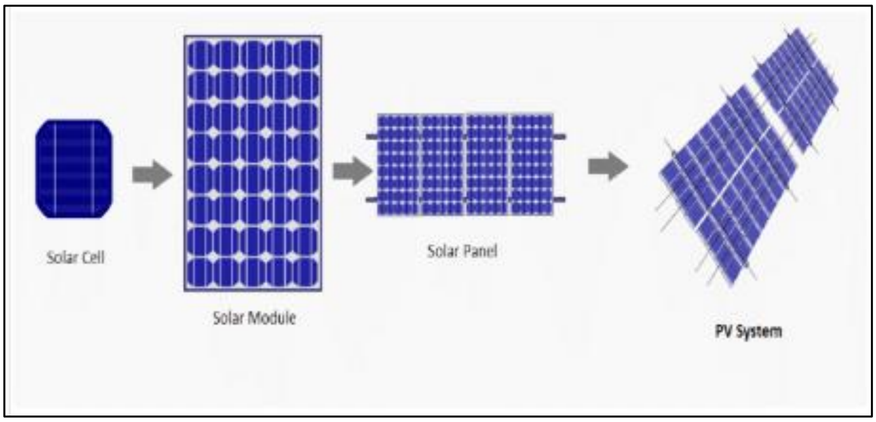

Figure I.5 Model of photovoltaic generator[15].

I.1.7 Connections Modules

1) **Series Connection of Modules**

Intention: Increasing the system's voltage.

Procedure: Connect the positive terminal of one module to the negative of the next, and the modules' voltages add up while the current remains the same[16].

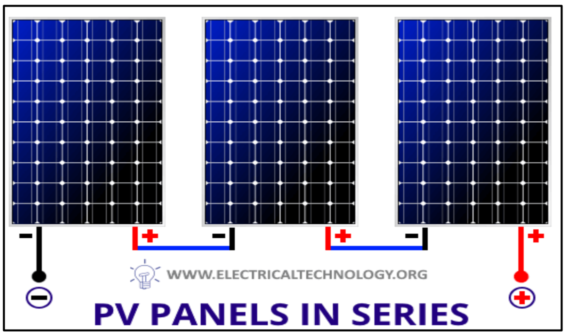

Figure I.6 Series Connection of Modules [17].

2) **Parallel Connection of Modules**

Intention: Increasing the system's current.

Procedure: Connect the positive terminals of several modules together and the negative terminals together. The current of the modules adds up, while the voltage remains the same as that of a single module[16, 18].

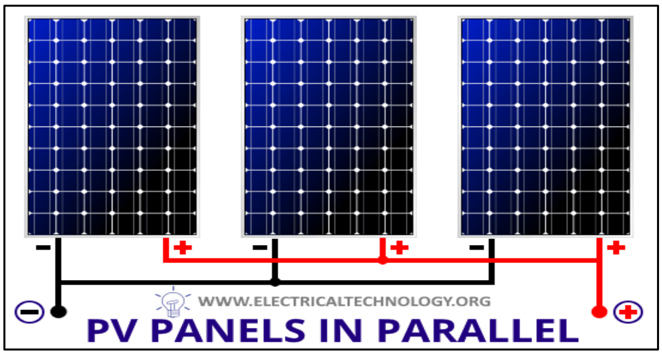

Figure I.7 Parallel Connection of Modules [17].

3) Series-Parallel Connection of Modules – Mixed Combination

When we need to generate large amounts of power in the gigawatt range for large PV systems, we need to connect modules in series and in parallel. In large PV systems, modules are first connected in series, known as a "PV module string", to achieve the required voltage level, and then many such strings are connected in parallel to achieve the required current level for the system[18].

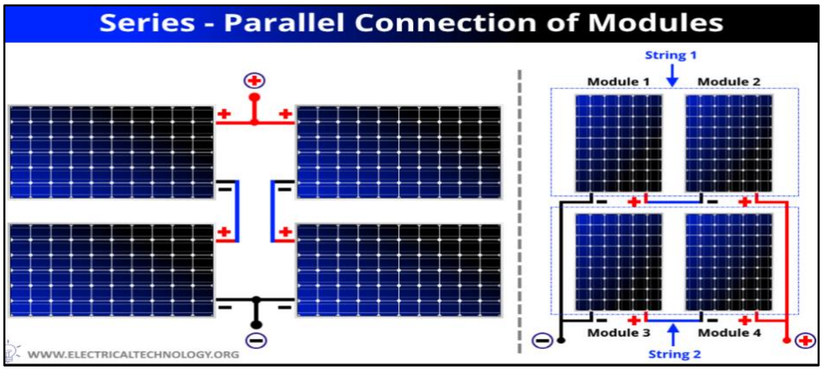

Figure I.8 Series-Parallel Connection of Modules – Mixed Combination [17].

I.1.8 Characteristic parameters of a photovoltaic cell

Four parameters can be used to describe the characteristics of a photovoltaic cell:

1) Short-circuit current Isc (for Voc= 0)

The short-circuit current is the maximum current generated by the cell when short-circuited (**V_{oc} = 0**) for "full sun" illumination, and is directly proportional to the radiant energy received on the cell surface.

2) Open circuit voltage Voc (for Isc = 0)

The open circuit voltage (Voc) is the voltage across the cell's terminals when no load is connected, resulting in a current (I) of zero.

3) Maximum Power Point (MPP)

The aim of any user of a photovoltaic generator is to ensure that the energy produced is as optimal as possible. The P_{mp} point represents the point at which the power of the solar cells is at its maximum. This point of maximum power is linked to the maximum voltage Vmp and the optimum current Imp.

$$Pmp = Vmp \times Imp \qquad (I.2)$$

Where;

Pmp: maximum power point [W]

Vmp: maximum power voltage [V]

Imp: maximum power current [A]

4) Fill factor (FF)

This is a significant parameter in the assessment of the performance of a solar cell. It is calculated as the ratio of the maximum power of the solar cell to the product of the open-circuit voltage (Voc) and short-circuit current (Isc).

$$FF = \frac{P_{PPM}}{I_{sc} \times V_{co}} \qquad (I.3)$$

Where;

Voc: open circuit voltage [V]

Isc: short circuit current [A]

5) Efficiency of a photovoltaic cell

Conversion efficiency is the most important parameter in solar cells. It expresses the cell's ability to efficiently convert photons of incident light into electrical current. It is calculated as the ratio between the output power Pout and the input power of the cell Pin (incident solar irradiance).

$$\eta = \frac{P_{out}}{P_{\text{in}}} = \frac{I_{cc} \times V_{oc} \times FF}{P_{\text{in}}} \qquad (I.4)$$

Where;

Pout: cell output power [W]

Pin: cell input power [W]

Voc: Open circuit voltage [V]

I.2 Advantages and disadvantages of photovoltaic systems

It's critical to weigh the benefits and drawbacks of installing solar systems in order to make well-informed judgments. While they offer a clean and renewable energy solution, there are certain limitations and considerations that need to be taken into account to ensure optimal performance and cost effectiveness.

I.2.1 The Advantages of photovoltaic systems

- Installing photovoltaic solar panels with the aim of achieving self-consumption is the first step towards independence from traditional energy suppliers;
- Solar energy is inexhaustible and non-polluting;
- The energy is clean and does not emit any greenhouse gases;
- Solar systems boost rural areas, especially in developing countries without electricity;
- multitudes of uses (photovoltaic, thermodynamic, etc.);
- Solar energy is available everywhere and can supply electricity close to where it is generated. This eliminates the need for long-distance transmission and avoids the losses associated with transmission lines;
- Three operating modes available (stand-alone, grid connected and hybrid).

I.2.2 The disadvantages of photovoltaic systems

- The investment cost of a solar installation is relatively high;
- The photovoltaic system requires good control to extract its maximum power at all times and under any conditions;
- The production of photovoltaic modules requires advanced technology and substantial investment;
- Solar power is an intermittent energy source;
- Installation of photovoltaic system requires considerable space;
- The efficiency of photovoltaic cells decreases over time, generally speaking, photovoltaic panels lose 1% of their efficiency every year.

I.3 The other categories of renewable energy sources

Wind, hydroelectric, biomass and geothermal energy are the many categories of renewable energy sources that are currently recognized. The primary benefit of using renewable energy sources is that they don't contribute to atmospheric pollution or the production of greenhouse gases like carbon dioxide and nitrogen oxides, which cause global warming.

I.3.1 Wind turbine energy

The concept of harnessing wind power goes back thousands of years. The Egyptians used wind power to propel boats down the Nile. Others used windmills to grind grain, pump water and cut wood in sawmills. They convert the wind's kinetic energy into clean, renewable electricity. Wind power generally takes two different forms: onshore wind farms, which are large wind turbine installations located on land, and offshore wind farms are installations located off the coast of the sea[19].Wind energy turns two or three propeller-shaped blades around a rotor. The rotor is connected to the main shaft, which turns a generator to produce electricity.

The fundamental formula for calculating the power available in the wind is:

$$P = 1/2 . S . \rho . V^3 . Cp \qquad (I.5)$$

Where;

- P: the power available in the wind (in watts, W);
- S: the area of the wind turbine blades (in square meters, m^2);
- ρ: the air density (in kilograms per cubic meters, kg/m^3);
- V: the wind speed (in meters per second, m/s);
- Cp: the power coefficient, which represents the efficiency of the wind turbine in capturing the wind's energy.

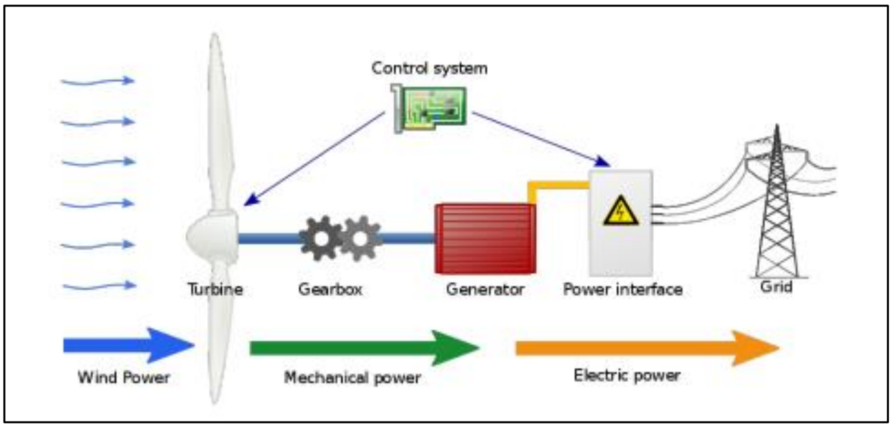

Figure I.9 Schematic of a wind energy conversion chain [19].

I.3.2 Hydroelectric energy

Hydroelectric power, or hydropower, is a renewable form of electrical energy obtained by converting the hydraulic energy of various natural water flows into electricity. The kinetic energy of the water flow is transformed into mechanical energy by a turbine, then into electrical energy by an alternator. For storage dams, the amount of energy available over a given period in the water reserve of a dam depends on its volume, natural inflows and outflows over the period and the head. For run-ofriver dams, the amount of energy produced is directly linked to the flow rate (m3/s, m3/h, m3/day, m3/year)[5, 20].

There are three types of turbines. The most suitable type of turbine is selected by calculating the specific speed (ns):

- The Pelton turbine, adapted to high heads, with a bucket wheel, invented by Lester Allan Pelton in 1879. It is designed for heads of over 200 meters.

-The Francis turbine, designed for medium to high heads, with a single or double impeller. Designed by James B. Francis in 1868.

-The Kaplan turbine, invented in 1912, perfectly suited to low heads and high flows, with a propeller-type impeller, like that of a boat. Viktor Kaplan developed a propeller wheel whose blades can be blades can be adjusted to suit the flow rate required[21].

The power of a hydroelectric power plant can be calculated by the following formula:

$$P = Q.H.g.r \tag{I.6}$$

Where;

- P: power in (Kilowatt);
- Q: average flow measured in cubic meters per second;
- H: fall height in meters (m);
- g: gravity constant nearly 9.8 (m/s2);
- r: Central efficiency (between 0.6 and 0.9).

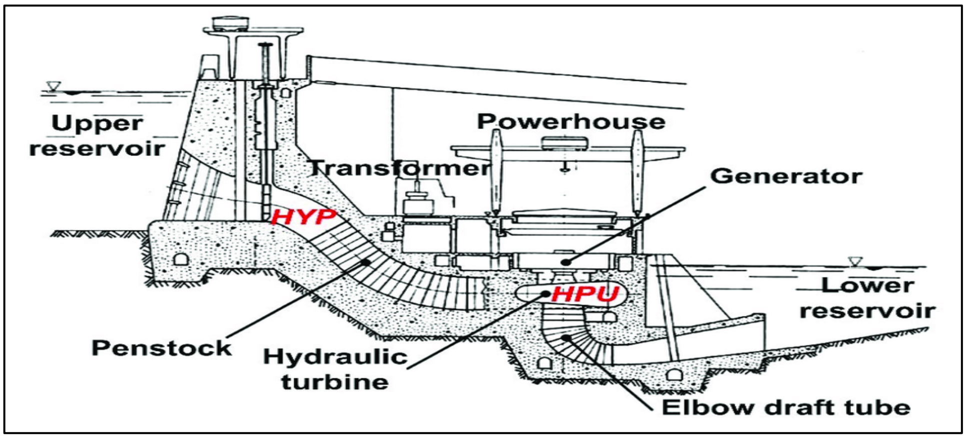

Figure I.10 Schematic view of a hydroelectric power plant: Hydro Power Unit (HPU) and Hydraulic Passage (HYP) [7].

I.3.3 Biomass energy

All organic material derived by plants, including algae, trees, and crops is referred to as biomass. As a result, biomass comes from a variety of sources, such as organic waste streams, forestry and agricultural waste, and crops cultivated for energy plantations, which provide heat, fuels, and electricity[5]. Biomass energy has a far greater resource potential than the world's present energy use. However, because solar energy has a low conversion efficiency (less than 1 percent), it takes a lot of space to manufacture contemporary energy carriers in significant quantities.

I.3.4 Geothermal energy

The stored thermal energy content of the rock and associated fluids under land masses that can be accessed by drilling is typically used to characterize a geothermal resource. [22]. Independent of the weather or environment, geothermal energy is a base load energy source that is always available[22, 23]. It has been used in several countries in the agricultural sector to heat greenhouses.

In Algeria, hot water wells which had been used for human consumption and irrigation for several decades, were only used to heat agricultural greenhouses from the 1970s, making a relatively modest contribution of geothermal energy to the development of the agricultural sector. Greenhouse heating began to be applied in the early 1950s in Holland and Belgium, such as Italy, France and Spain have until now considered that approvable conditions did not justify such a production tool[24].

I.4 Advantages and disadvantages of renewable energy sources

I.4.1 The Advantages of renewable energy sources

- They are much more environmentally friendly than traditional methods of energy production based on fossil fuels;
- The undeniable fact remains that solar and wind power production with minimal labor costs at their operational phases;
- Unlike traditional fuel sources, which are owned by units, renewable energy sources are available to most of the world's population. This is true not only in terms of the abundance of the sources themselves (sun, wind, geothermal energy), but also the economic viability of generating the energy itself. Already today, many homeowners can afford to have their own power stations to meet their electricity needs[25];
- Partial autonomy of the local system in the event of a major incident on the network - Remote control of the system.

I.4.2 The Disadvantages of renewable energy sources

- For some energy sources, such as wind and solar power, there is a high degree of intermittency, poor predictability and little or no controllability;

- Low capacity to participate in rebuilding the network, risk of uncontrolled islanding;
- Little or no contribution to adjusting the frequency and voltage of the electricity network.

Conclusion

This chapter provided an overview of photovoltaic energy, starting with the definition and history of the photovoltaic system, explaining the photovoltaic effect and the principle of photovoltaic conversion. It discussed the different types of photovoltaic cells, their characteristics and the different connections of the modules and the advantages and disadvantages of the photovoltaic system. In addition, a brief overview of other categories of renewable energy and their advantages and disadvantages.

CHAPTER II: MODELING AND CONTROL OF PV SYSTEM WITH DIFFERENT MPPT TECHNIQUES

Introduction

Solar energy has shown promising results in the search for a solution to many problems. Harnessing solar energy using PV modules has its own problems, which arise from the change in atmospheric conditions. These changes in climatic conditions have a very significant impact on the efficiency and power of the PV modules. To increase their effectiveness, a great deal of study has been conducted. A number of approaches for tracking the maximum power point of a PV module have been presented to overcome the problem of efficiency.

This chapter begins with the modelling of a photovoltaic system to obtain its two characteristics, P-V and I-V, and the study of the influence of radiation and temperature on the specific panel used in this study. followed by an examination of different types and classifications of converters, specifically the modeling of the DC-DC boost converter. An introduction to maximum power point tracking (MPPT) control follows, including its definition, methods and the characteristics of different MPPT methods. The chapter ends by comparing the MPPT methods presented in this study.

II.1 Model of a photovoltaic cell

II.1.1 The basic cell model

The basic equivalent diagram of a photovoltaic cell with an ideal PN junction consists of an ideal current source connected in parallel with a real diode. The diode represents the PN junction whose polarization determines the voltage[26, 27].

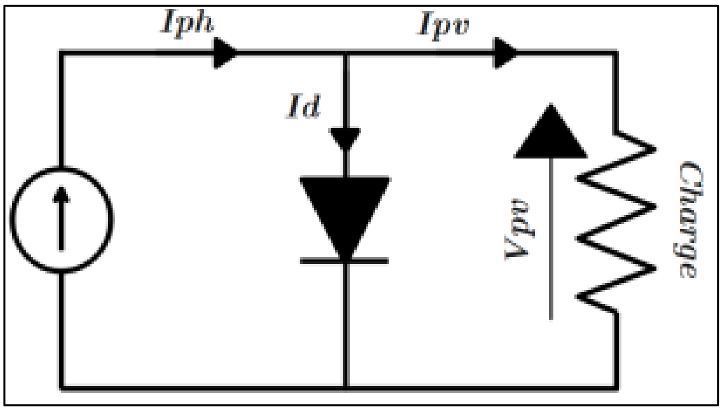

Figure II.1The simplest equivalent diagram of the PN junction photovoltaic cell.

The characteristic equation is deduced directly from Kirchhoff's law:

$$Ipv = Iph - Id \qquad (II.1)$$

Where;

Ipv: Current delivered by the diode [A]

Iph: Solar cell photocurrent [A]

Vpv: Voltage supplied by the PV cell [V].

Id = diode current. The diode current is given by the following equation: law:

$$I_d = I_s\left(e^{\frac{qv_{pv}}{mkT}} - 1\right) \quad \text{(II.2)}$$

Where;

Vpv: Voltage supplied by the PV cell [V]

Is: Reverse saturation current [A]

Iph: Solar cell photocurrent [A]

Id: Current through the diode [A]

Ipv: Current delivered by the diode [A]

q: Electron charge [1.602 × 10-16 C].

k: Boltzmann's constant [1.381 × 10-23 J/K].

T: Junction temperature [K]

m: diode quality factor.

II.1.2 The single-diode model

The simplest representation of a solar cell is the single diode model. It consists of a current source in parallel with a diode. The parameters required are the short-circuit current (Isc), the open-circuit voltage (Voc) and the diode ideality factor (a). The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation.

The presence of recombination losses results in non-ideal ideality factors. The basic model is improved for accuracy by the introduction of the series resistance (Rs), but it does not prove to be efficient under temperature variations. To overcome this drawback, an additional shunt resistance (Rsh) is introduced. This increases the parameters to a considerable level and the calculations are increased. Although Rsh is added, the model fails at low irradiance conditions[28].

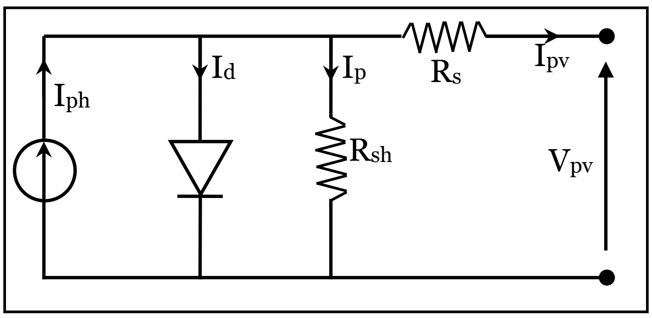

Figure II.2 Equivalent circuit of Single Diode model.

The characteristic equation is deduced directly from Kirchhoff's law:

$$Ipv = Iph - Id - Ish \qquad (II.3)$$

Where;

Ish: shunt current [A]

The shunt current is:

$$I_{sc} = \frac{V+R_S I_{pv}}{R_{sh}} \qquad (II.4)$$

Where;

Rsh: shunt resistance to the diode [ohm];

R_S: series resistance to the diode [ohm].

The I-V and P-V characteristic of this module is represented by the following equations as follows:

$$I = I_{ph} - I_o\left(\exp\frac{q(V+R_S I)}{AKTN_s} - 1\right) - \frac{(V+R_S I)}{R_{sh}} \qquad (II.5)$$

Where;

V: is the voltage applied to the diode [V];

A: is the ideality factor [A].

$$\mathrm{I_{ph}} = \mathrm{I_{sc}} * \frac{G}{1000} * [1 + \mathrm{a} * (\mathrm{T} - \mathrm{T_{Ref}})] \qquad (II.6)$$

Where;

Isc: is the short-circuit current of the solar cell under reference conditions [A];

G: is the solar irradiance [W/m²];

a: Temperature coefficient of Isc;

T: is the current temperature of the cell [K];

T_{Ref}: is the reference temperature of the cell [K].

$$I_0 = I_{rs}\left(\frac{T_c}{T_{cRef}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{A\cdot K}\right)\left(\frac{1}{T_{cRef}} - \frac{1}{T_c}\right)\right] \qquad (II.7)$$

Or

$$Irs = \frac{I_{sc}}{\left(\exp\frac{q\text{Voc}}{AKTN_s} - 1\right)} \tag{II.8}$$

Where;

Irs: is the current of reverse saturation to the diode;

Io: is the diode saturation current;

E.g.: is the band gap energy in the solar cell solar cell;

Voc: is the open circuit voltage of the solar cell under reference conditions [V].

II.1.3 The Characteristics of Solar PV

The output of the PV system is non-linear and depends primarily on irradiation and temperature. It depends on other parameters like series and shunt resistances, number of series and shunt cells, density of accumulated dust on SPV panel[29]. These previous equations allow us to model and obtain the two characteristics of the PV system: power-volage and current-voltage

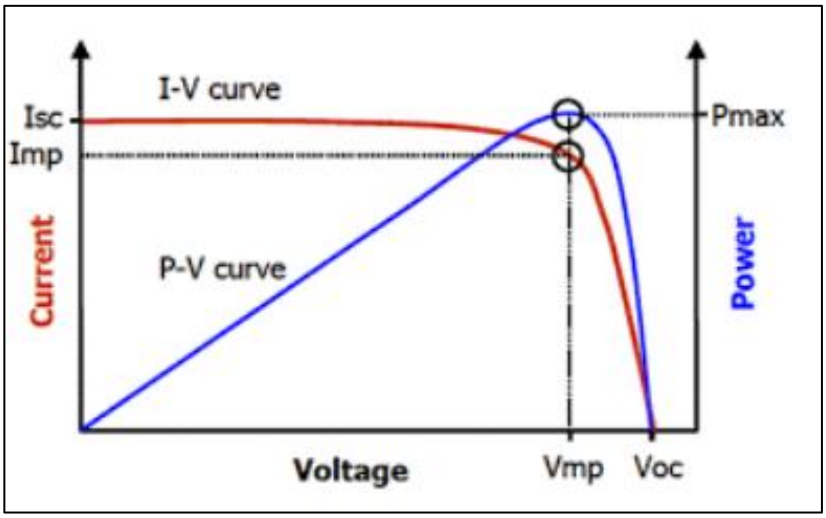

Figure II.3 Typical I-V and P-V characteristics of photovoltaic cell.

II.1.4 Influences of atmospheric criteria

To compare our model more closely with reality, we need to look at how certain parameters affect the I-V and P-V characteristics.

a) Influence of irradiation

For different levels of solar irradiance ranging from 200 W/m² to 1000 W/m² and constant temperature 25°C, the current produced by the solar cell is practically proportional to the solar irradiance G. On the contrary, the open circuit voltage decreases only slightly with the irradiance. This means the optimum power of the cell is practically proportional to the irradiance.

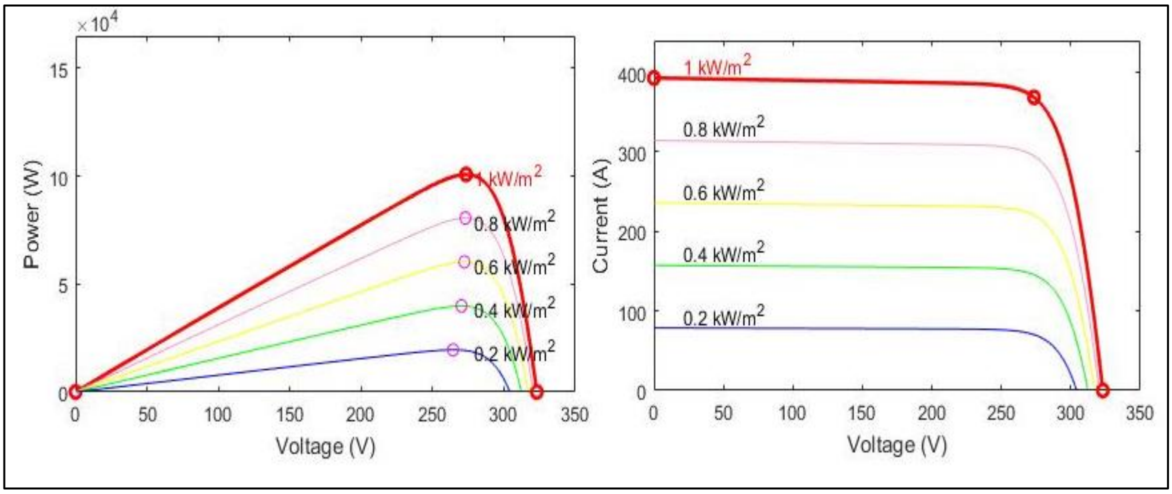

Figure II.4 Influence of irradiation SunPower SPR-315E-WHT-D array.

b) Influence of temperature

The figure illustrates the behavior of a module under fixed illumination of 1000W/m2 at temperatures ranging from 0°C to 75°C. It can be seen that at higher temperatures there is a slight increase in current, while the open circuit voltage decreases. This reduction in the open circuit voltage results in a reduction in the maximum power points.

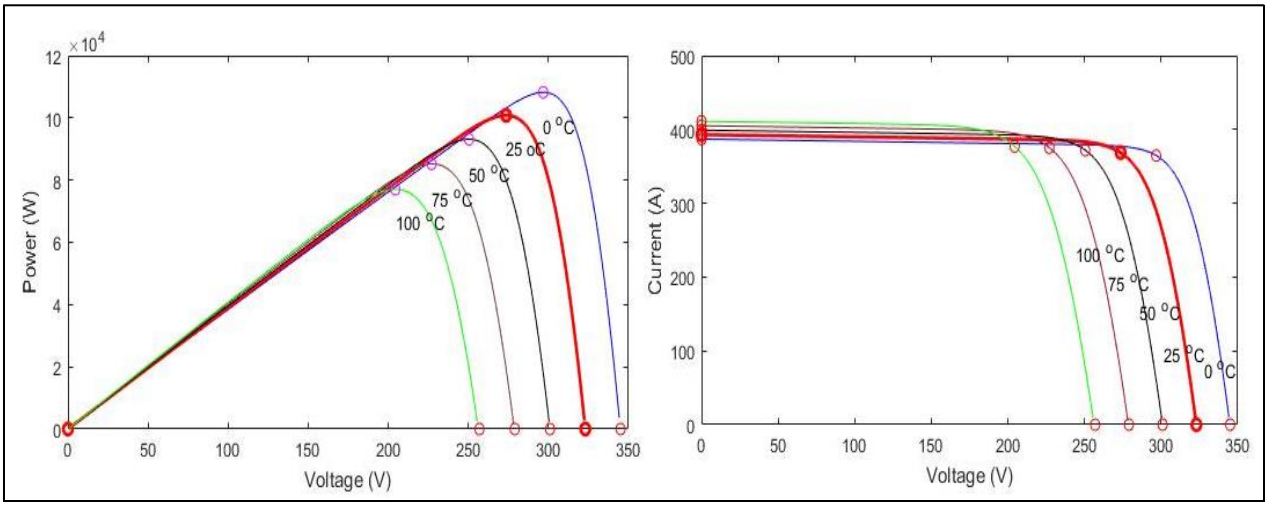

Figure II.5 Influence of temperature SunPower SPR-315E-WHT-D array.

Temperature and irradiance are therefore the two main parameters that modify the characteristics of a PV generator. These two parameters must therefore be carefully considered when setting up a PV installation

II.2 DC-DC converters (Choppers)

The use of DC-DC converters makes it possible to control the power in DC circuits with great flexibility and high efficiency, which in our case allows us to seek the optimum operating point. The switching circuits are made up of capacitors, inductors and switches. Ideally, they consume no energy at all[30]. The switch is made with a semiconductor device, usually a MOSFET transistor operating in (off/saturated) mode.

When the semiconductor device is blocked, its current is zero and therefore its power dissipation is zero. power dissipation. When the device is saturated, the voltage drop across its terminals is close to zero, so the power dissipated is very low[31].

By varying the duty cycle of the switching element, the output voltage is regulated. For this reason, all power conversion must take place around the energy storage components (inductors and capacitors) and the switches.

During switching operation, the transistor will be switched at a constant frequency f_S with a closing time equal to DT_s and an opening time equal to $(1 - D)T_S$.

- T_S is the switching period, which is equal to $1/f_S$
- D is the duty cycle of the switch ($D \in [0,1]$).

II.2.1 Types of DC/DC converters

The three basic topologies of DC/DC converters that are as follows

- Buck converter (step-down)
- Boost converter (step-up)
- Buck-boost converter (step-down or step-up)

II.2.2 Buck Converter (step-down)

This DC/DC converter is used to adapt the operating point of the panel to the load when the output voltage of the converter is lower than the nominal operating point of the PV generator[32]. In the case of a buck converter, its input voltage can be expressed as follows:

$$Vi = \frac{V_S}{D} \qquad \text{(II.9)}$$

Where;

Vi: input voltage.

Vs: output voltage.

D: Converter Duty cycle.

Principle of operation

The step-down converter uses a K-switch (commutator) controlled without isolation between the input source and the output (Figure II.6). The operation of the converter can be divided into two configurations[33].

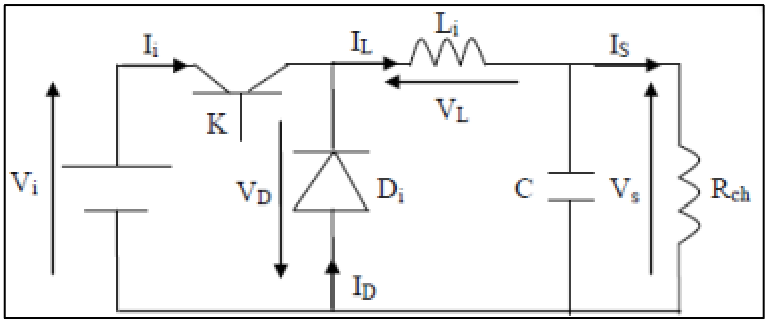

Figure II.6 Basic schematic of a Buck converter.

ON state

In the ON state, switch K is closed (Figure II.7) and the voltage across the inductor is:

$$V_L = Vi - Vs \tag{II.10}$$

The I_L current does not increase instantaneously, but linearly with a rate of increase imposed by the Li inductor.

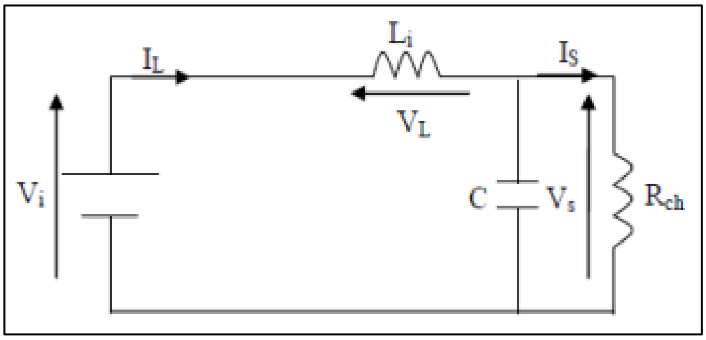

Figure II.7 Buck converter ON state.

OFF state

In the blocked state, switch K is open (figure II.8) and the diode becomes conductive to ensure the continuity of the current in the inductor. The output voltage is:

$$Vs = -V_L \tag{II.11}$$

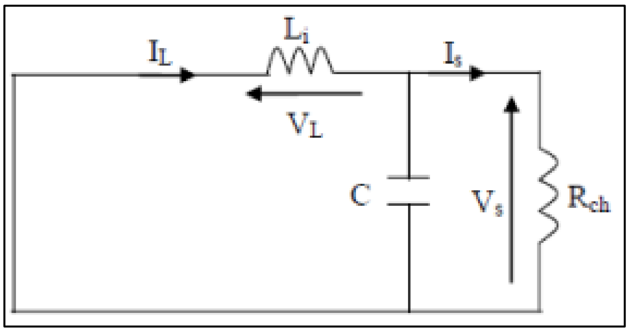

Figure II.8 Buck converter OFF state.

II.2.3 Boost converter (step-up)

A boost converter (also called a step-up chopper) is a device that increases the input DC voltage to a higher output DC voltage. The ratio between the input and output voltages can be expressed as:

$$V_S = \frac{V_i}{1 - D} \tag{II.12}$$

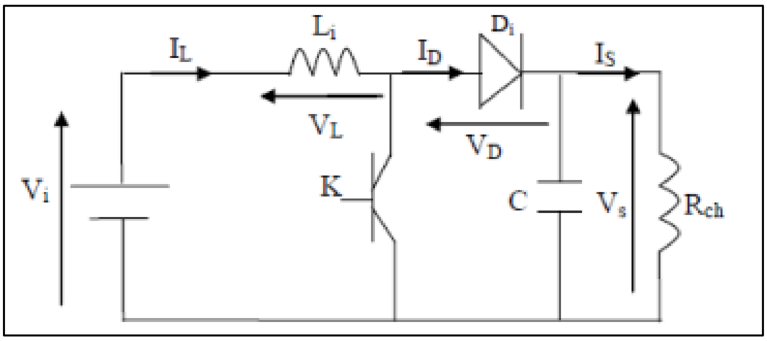

Figure II.9 Basic schematic of a Boost converter.

Principle of operation

As the circuit is supplied by a voltage source Vi, the operation of a boost converter can be divided into two distinct phases, depending on the state of the switch**.**

ON state

When the switch is closed (0 < t < DT) (Figure II.10), the current in the inductor increases and energy is stored in the form of magnetic energy. The diode is then blocked and the load is consequently disconnected from the supply.

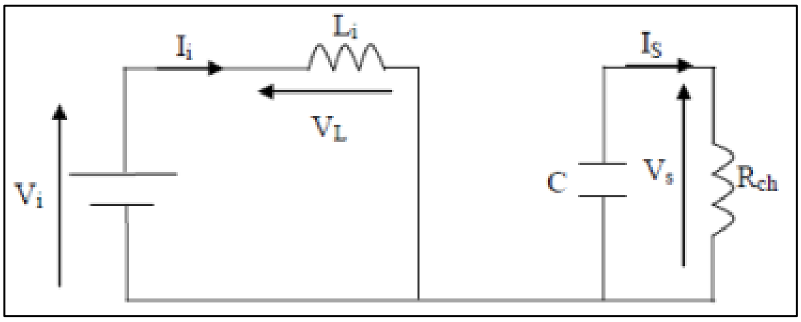

Figure II.10 Boost converter ON state.

OFF state

At the time t = DT, switch K opens (figure II.11), the Electro-Motive Force of the inductor is added to that of the alternator by placing the inductor in series with the alternator (voltage boost effect). The diode is then conducting and current flows through the inductor, the capacitor and the load. The result is a transfer of stored energy to the capacitor.

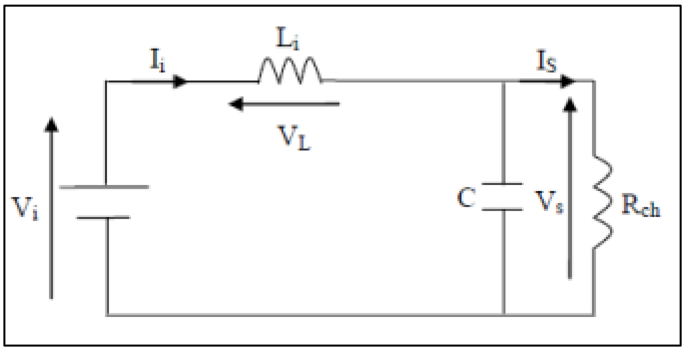

Figure II.11 Boost Converter OFF state.

II.2.4 The modeling of the Boost converter (step-up)

The boost converter used in this study consists of an input capacitor CI, an inductor L and an output capacitor CO. The values of these three parameters are calculated using the following three equations:

- Induction (L)

$$L = \frac{VmpDmp}{2dIFs} \quad (II.13)$$

Where;

Vmp = maximum power voltage;

Dmp = Duty cycle of the maximum power;

dI= the current ripple;

Fs = the switching frequency.

- Input capacity (C1)

$$C1 = \frac{4VmpDmp}{dV_I R_I Fs} \tag{II.14}$$

Where;

R_I = Input resistance;

dV_I = ripple voltage.

- Output capacity (C2)

$$C2 = \frac{2V_o Dmp}{dV_o R_o Fs} \tag{II.15}$$

Where;

V_o = output voltage;

dV_o = ripple voltage;

R_o = output resistance.

II.3 Maximum POWER POINT Tracking (MPPT)

Today, the development of this type of energy is still in its beginnings, due to the high price of PV generators and the low efficiency of the photon-electron conversion systems used. As we have seen, PV energy comes from the direct conversion of photon energy contained in solar radiation into electrical energy. In fact, both studies and simulations have shown that this conversion is a highly variable function, depending on irradiance and temperature, and also on the load connected to the PV generator.

The most cost-effective way to improve the performance of photovoltaic generators is to keep them operating at their maximum power point, independent of environmental conditions.

II.3.1 Principle

Specific control laws are implemented to ensure that a solar power system operates at its maximum power point. This type of control is commonly known as 'maximum power point tracking' (MPPT). The main principle of these control techniques is to find the point (MPP) while achieving optimal matching between the generator and its load for efficient power transfer. The MPPT controller is connected to a static converter that facilitates the adaptation between the solar power generator and the load, ensuring that the generated power is maximized and transferred directly to the load[34-36].

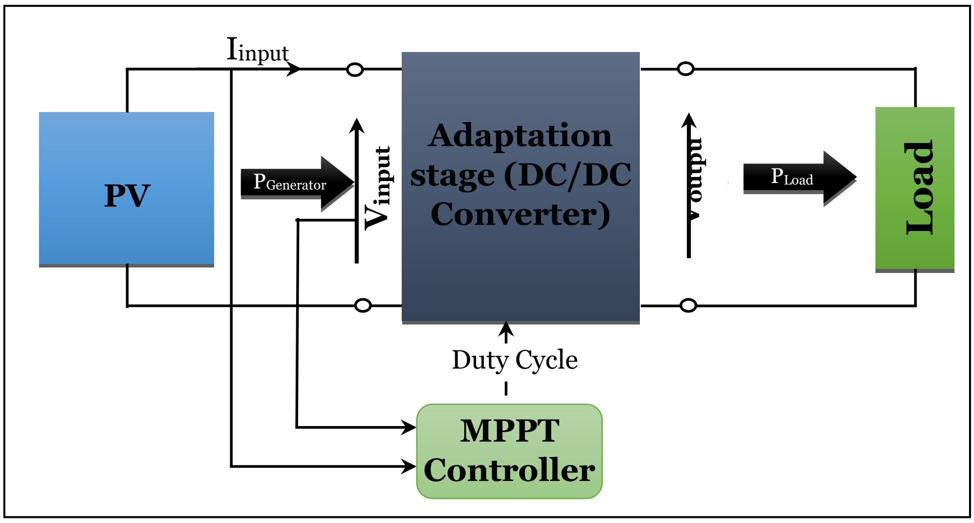

Figure II.12 Elementary photovoltaic conversion chain with MPPT.

II.3.2 Evaluation criteria for MPPT control

- **the efficiency**

The actual power supplied by the GPV depends on the controls used in the inverter (MPPT, voltage control, direct connection, etc.). The resulting MPPT is used to measure the efficiency of the converter control. The MPPT determines the % power loss of the PV module in relation to the maximum power that can be produced[37].

$$\eta_{\text{MPPT}} = \frac{\text{Peff}}{\text{Pmax}} \tag{II.16}$$

Where;

η_{MPPT}: Efficiency of the operating point

P_{eff}: the power actually supplied by the GPV

Pmax: The maximum power potentially available at the output of a PV panel.

- **Simplicity & Cost**

The MPPT controller must be simple in design and have a reasonable operating cost so that its use compensates for the additional expenditure involved.

- **Dynamic response**

The MPPT controller must have good dynamic performance to control the adaptation stage and ensure that a new MPPT is found as quickly as possible following changes in illuminance or temperature.

- **Flexibility**

Whatever the operating conditions, the MPPT controller must be accurate and stable. It must be designed to work universally with panels of different technologies, with precision and robustness, without the need for major modifications.

- **Competitive over a broad power range**

The MPPT control used must follow the PPM generated by the photovoltaic module, whatever the level of insolation. The MPPT control is considered competitive if the MPP is achieved with a static error, corresponding to the position of the operating point [37, 38].

II.3.3 The Conventional MPPT algorithms

Several techniques are used to track the Maximum Power Point (MPP). Some of the popular algorithms and that will be used in the study are:

- Perturb and Observe Method
- Incremental Conductance Method
- PID controller (Proportional-Integral-Derivative)

a) Perturb & Observe Algorithm(P&O)

The most commonly used method is Perturb and Observe in practice due to its simplicity and ease of implementation[39]. In this process, the output voltage of the solar panel is periodically disturbed and then the output power is with the previous cycle. Corrective action is then taken to force the voltage towards the maximum operating output voltage. The operational point's location and the perturbation's direction can be ascertained by the comparison[28, 40].

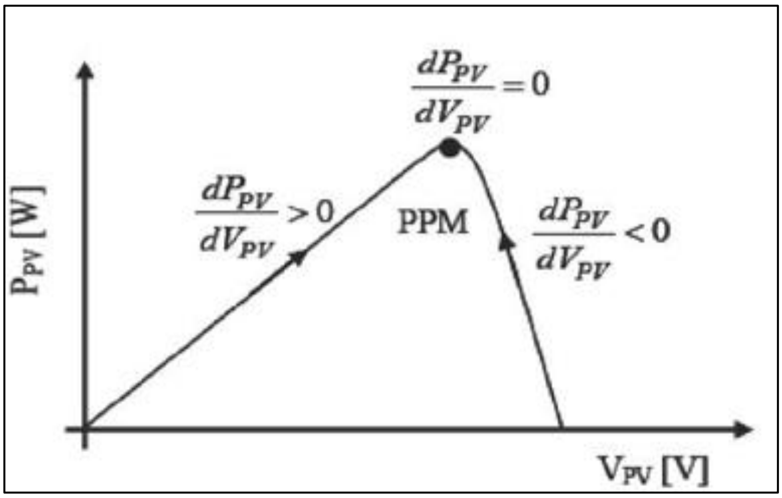

Figure II.13 Principle of P&O method [28].

Figure II.13 shows that increasing (decreasing) the voltage increases (decreases) the power when operating to the left of the MPP and decreasing the voltage increases (decreases) the power when operating to the right of the MPP. Therefore, if the power is increased, the subsequent disturbance must be kept the same in order to reach the MPP, and if the power is decreased, the perturbation must be reversed. The process is repeated periodically until the MPP is reached. The system will then oscillate around the MPP. Oscillation can be minimized by reducing the step size of the perturbation. However, a smaller step size will slow down the MPPT[41].

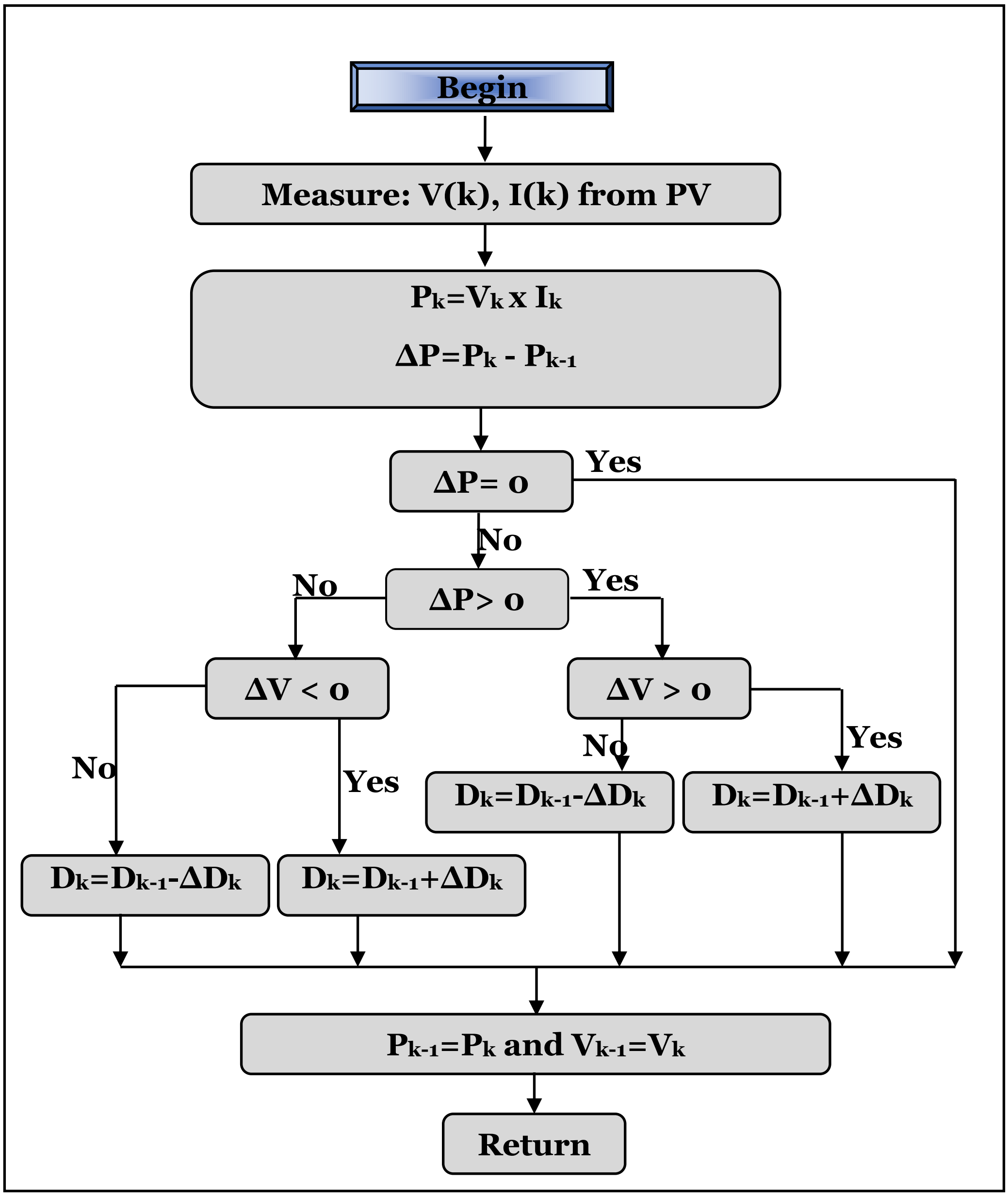

Figure II.14 Flowchart of the conventional Perturb and observe algorithm.

The algorithm for this control method is shown in (figure II.14) and its principle is as follows generating perturbations by adjusting the duty cycle D and observing the corresponding effect on the power received from the solar generator: When the rate of change of electrical power with respect to voltage (dpv / dVpv) is greater than 0, indicating an increase in voltage, the duty cycle is also increased.This is achieved by the equation D(k) = D(k-1) + δD, where δD is a constant used to increase the duty cycle. If the rate of change of electrical power with respect to voltage (dPpv / dVpv) is less than 0, implying a decrease in voltage, the duty cycle is reduced. This is achieved by the equation D(k) = D(k-1)- δD. By continuously adjusting the duty cycle based on the observed changes in power, this control method attempts to track and converge to the maximum power point of the solar generator[2].

b) Incremental Conductance (IC)

The principle of this algorithm is based on the knowledge of the conductance value G=I/V and the conductance increment (ΔG) to deduce the position of the operating point in relation to the Maximum Power Point (MPP). In this method, the derivative of the panel's output power is evaluated in a different way. It is calculated as a function of voltage V and dV, current I and dI. This derivative is canceled at the point of maximum power, positive to the left of the MPP and negative to the right.

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} = 0 \qquad \text{(II.17)}$$

$$\frac{dI_{pv}}{dV_{pv}} \cong \frac{\Delta I_{pv}}{\Delta V_{pv}} = -\left(\frac{I_{pv}}{V_{pv}}\right) \qquad \text{(II.18)}$$

Incremental conductance is much less commonly defined. By the variation of the current by that of the voltage between two points in time (ΔG = dIpv / dVpv).

$$\begin{cases} \frac{dP_{pv}}{dV_{pv}} = 0 \\ \frac{dP_{pv}}{dV_{pv}} > 0 \\ \frac{dP_{pv}}{dV_{pv}} < 0 \end{cases} \begin{cases} \frac{\Delta I_{pv}}{\Delta V_{pv}} = -\left(\frac{I_{pv}}{V_{pv}}\right) \text{ at } MPP \\ \frac{\Delta I_{pv}}{\Delta V_{pv}} > -\left(\frac{I_{pv}}{V_{pv}}\right) \text{ left of MPP} \\ \frac{\Delta I_{pv}}{\Delta V_{pv}} < -\left(\frac{I_{pv}}{V_{pv}}\right) \text{ right of } MPP \end{cases} \qquad \text{(II.19)}$$

The slope of the power curve of the photovoltaic is zero at MPP, positive on the left and negative on the right. Equation II.19 shows that the MPP s reached when dIpv/dVpv = Ipv/Vpv.

- If dIpv/dVpv > - Ipv/Vpv, the operating point is to the left of the MPP on the P-V curve.
- If dIpv/dVpv < - Ipv/Vpv, the operating point is to the right of the MPP on the P-V curve.

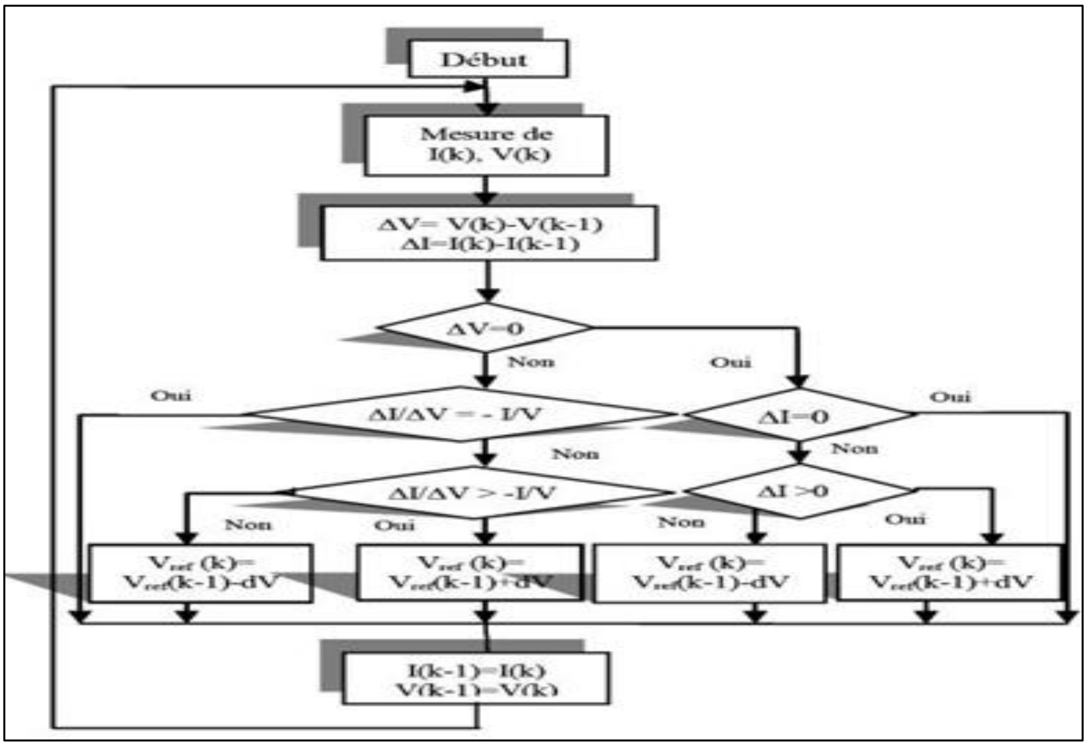

Figure II.15 Flowchart of the conventional incremental conductance algorithm.

The MPP can then be calculated by comparing the instantaneous conductance (I / V) with the incremental conductance (Δ I/ ΔV) as shown in the flow chart in Figure II.15.

The size of the increment determines the tracking speed of the MPP. Fast tracking can be achieved with larger increments, but the system may not track exactly to the MPP and may oscillate around it.

c) PID controller (Proportional-Integral-Derivative)

The most often used controller in industry is a PID controller. It combines three distinct controller types, indicated by P, I, and D, respectively: proportional, integral, and derivative. It is a feedback control system that needs to be activated by an error signal. Based on the value, it generates a control signal[42]. The PID controller is formulated in,

$$u(t) = kp.\, e(t) + ki \int_0^t e(t)\, dt + kd \frac{d}{dt} e(t) \qquad \text{(II.20)}$$

Are the PID gains, where kp is the proportional gain, ki is the integral gain and kd is the derivative gain. For the actual implementation of the PID controller, the error must be calculated. The PID error is the slope of the dP/dV curve. This is because the PID controller tries to reduce the error to zero. The slope of the curve at the MPP is zero. dP/dV is calculated continuously at any temperature and irradiance, so the PID controller is able to track the MPP effectively under rapidly changing external conditions.

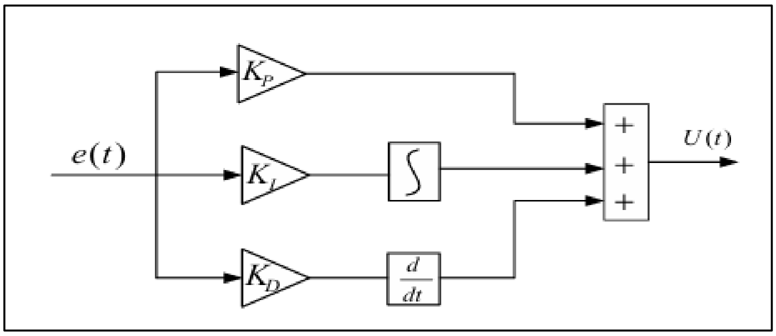

Figure II.16 PID Controller structure

The PID controller controls the error between the GPV output voltage and the reference voltage, which helps to reduce power consumption. The reference voltage, calculated by the following equation[43]:

$$\mathrm{Vref} = \mathrm{Se}\left(\frac{\mathrm{NsAKT}}{q}\log\left(\frac{\mathrm{Iph}-\ \mathrm{Iref}+\ \mathrm{Io}}{Io}\right)\right) \quad \text{(II.21)}$$

Where;

Se: is the number of series solar panel.

II.3.4 The improved MPPT method of P&O and IC

The conventional MPPT methods based on a fixed step size have a good performance, but they are characterized by a slow convergence. PV power fluctuates around the MPP, failing to operate in rapidly changing atmospheric conditions and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions[44, 45]. Therefore, starting from the basic principle of MPPT, in this project an improved **variable step size** IC and P&O are improved. The variable step size method improved is shown as follows:

$$D(k) = D(k-1) + N^* \left|\frac{dP}{dV - dI}\right| \quad \text{(II.22)}$$

Where;

D(k) and D(k-1) are the converter duty cycle at time (k) and the converter duty cycle at the previous time (k -1);

N is the scaling factor set at the sampling period to regulate the step size, which is manually set.

I(k), V(k) and P(k) are the PV array output current, voltage and power at the instant(k)

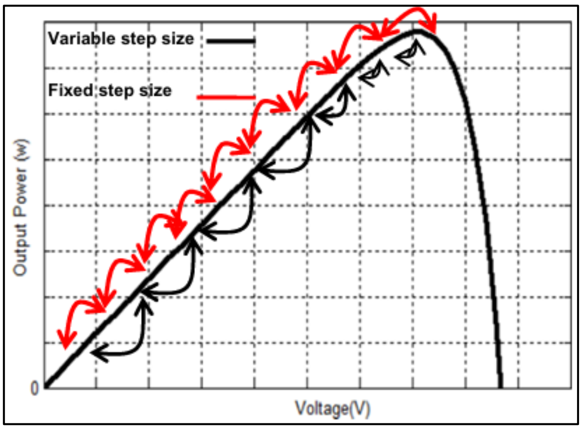

Figure II.17. Fixed and variable step size MPPT operation.

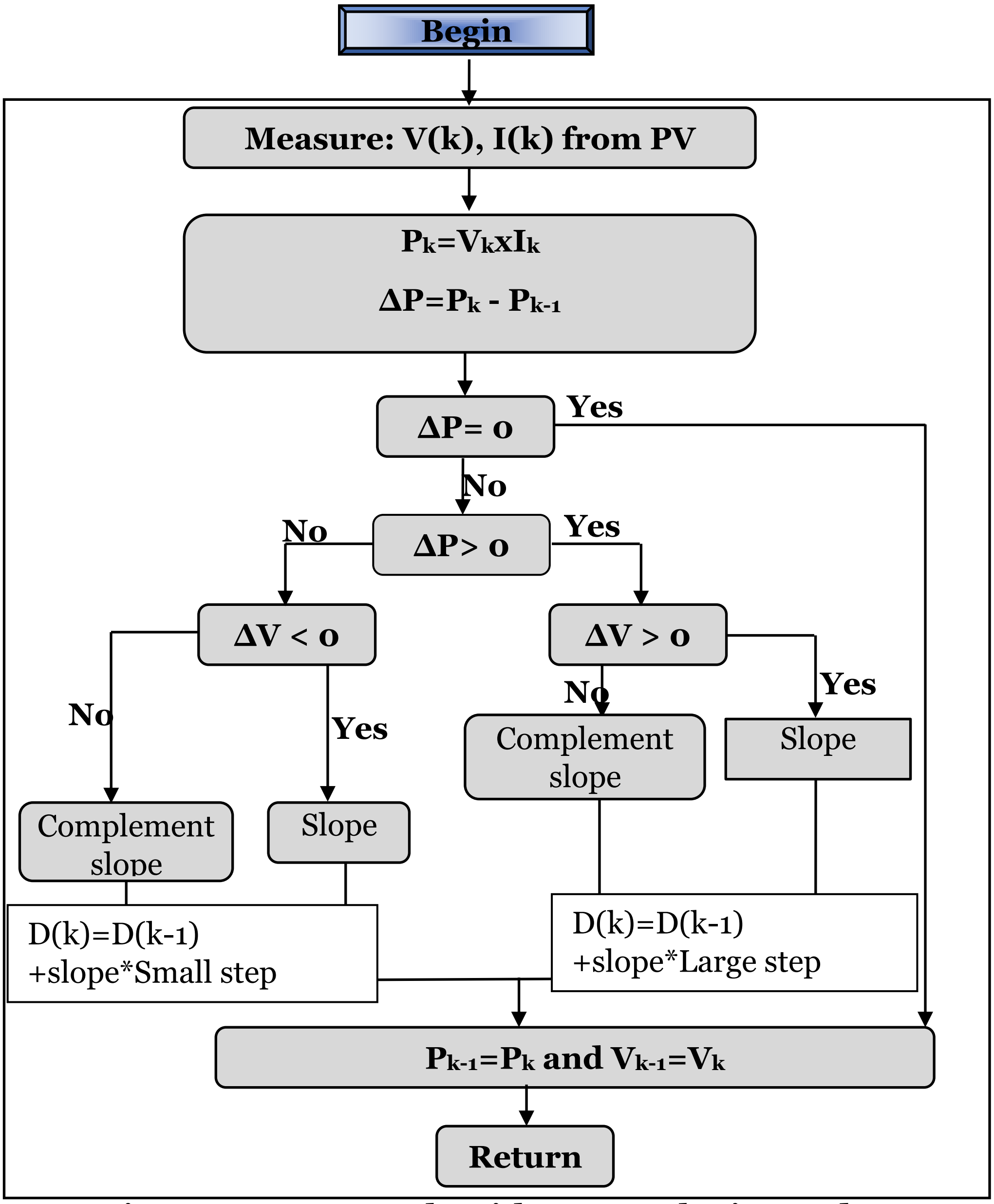

Figure II.18 MPPT Algorithm perturbation and observation with variable step.

With variable step size, the MPPT method becomes very dynamic (high step size to the right and left of the MPP, but very short step size in the proximity of the MPP and zero step size at the MPP)[45]. Throughout the simulation, variable-step solving modifies the step size. When a model's states change quickly, they decrease the step size to improve accuracy.

Figure II.19 Flowchart of the improved variable step size IC MPPT algorithm.

II.4 Comparison of MPPT techniques

The following table summarizes the main specifications of the various MPPT algorithms presented previously. We have evaluated and compared these algorithms in terms of technical knowledge of PV panel parameters, complexity, speed and accuracy. The validity of this comparison will be demonstrated in the next chapter.

Table II.1 Comparison of MPPT Methods.

MPPT Algorithms	P&O		IC		PID
	Fixed step	**Variable step**	**Fixed step**	**Variable step**	
Complexity	Low	Medium	Low	Medium	Medium
Accuracy	Low	Medium	Medium	High	High
Type of sensors used	Voltage Current		Voltage Current		Voltage
Identification of PV panel parameters	No required		No required		Yes required

Conclusion

This chapter provided the modelling of a photovoltaic system (basic cell model and single-diode model), the specifications and characteristics of the photovoltaic array used in this study and influence of parameters on array characteristics (irradiance and temperature). It discussed the different types of converters DC-DC, specifically the modeling of the DC-DC boost converter. In addition, an introduction to maximum power point tracking (MPPT) control, including its definition, methods and the characteristics of P-O, IC (conventional fixed step size and improved variable step size) and PID MPPT methods. Finally, a comparison between them.

CHAPTER III: SIMULATION RESULTS & DISCUSSIONS

Introduction

In photovoltaic systems, it's difficult to maintain the PPM for a variety of unpredictable conditions (fast changing of atmospheric conditions, shading, no linear characteristics…). In order to validate the effectiveness of the proposed techniques, a simulation under MATLAB / Simulink environment as a function of variations in irradiation and fixed temperature 25°C.

The results of each MPPT algorithm will be presented, discussed separately and a comparison between them. In addition, the whole system is simulated under different irradiance conditions and the results are presented and analyzed comprehensively.

III-1 Introduction to MATLAB

MATLAB is a matrix calculation program with simple syntax;

- ✓ Can be considered as a programming language suitable for scientific problems, with its specialized functions;
- ✓ Is an interpreter, as its instructions are interpreted and executed line by line;
- ✓ Has good graphical capabilities for presenting results or creating applications;
- ✓ Can be integrated with C or FORTRAN code;
- ✓ Runs in several environments such as UNIX/X Windows, Windows, Macintosh.

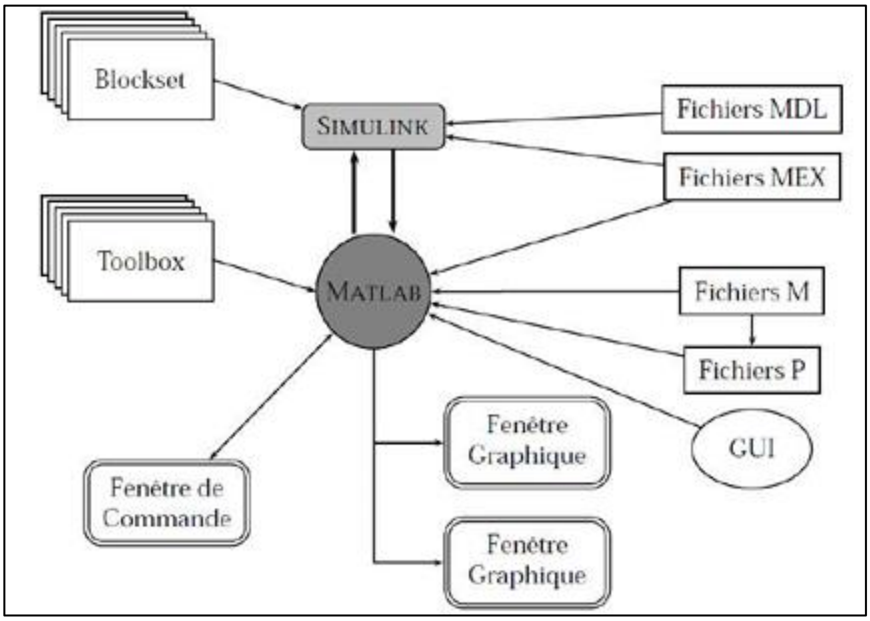

Figure III. 1 MATLAB environment.

- ✓ **Command window**: in this window, the user gives instructions and MATLAB returns the results;

- ✓ **Graph windows**: MATLAB plots graphs in these windows;
- ✓ **M files**: these are MATLAB language programs (written by the user);
- ✓ **P files**: pre-interpreted versions of M files;
- ✓ **Toolboxes**: these are collections of M files developed for specific fields of application;
- ✓ **Simulink**: this is the graphical extension of MATLAB for working block diagrams to model and simulate systems;
- ✓ **Blocksets**: collections of SIMULINK blocks developed for specific fields of application
- ✓ **MDL files**: these are files representing SIMULINK models;
- ✓ **MEX files**: executable modules created from C or FORTRAN sources;
- ✓ **GUI**: graphical user interface for creating applications based on MATLAB.

III-2 The Photovoltaic System

III-2-1 The Specifications of the photovoltaic array

The cells can be connected by increasing the number of cells in series and parallel according to the load requirement. The SunPower SPR-315E-WHT-D photovoltaic module was selected for this simulation. The array consists of 5 solar modules connected in series per string and 64 solar modules connected in parallel per string to produce a maximum power of 100KW in 25°C and 1000 W/m2. The electrical specifications of the photovoltaic array are given in Table III.1:

Table III. 1 PV Cell Specifications of SunPower SPR-315E-WHT-D array.

Parameters	Values
Maximum power (Pmax)	100 KW
Voltage at maximum power (Vmp)	273.5 V
Current at maximum power (Imp)	365.6 A
Open circuit voltage (Voc)	323 V
Short circuit current (Isc)	393 A
Temperature coefficient of Isc(a)	0.061694 ± 0.015% /Co

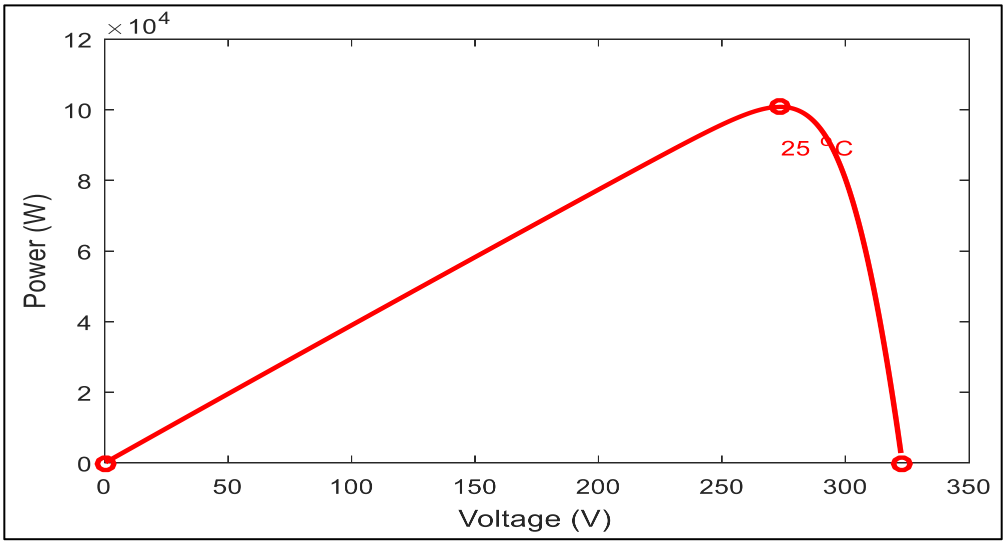

Figure III.2 Power-Voltage characteristics of a PV array fixed irradiation 1000W/m2 and temperature 25°C of SunPower SPR-315E-WHT-D array.

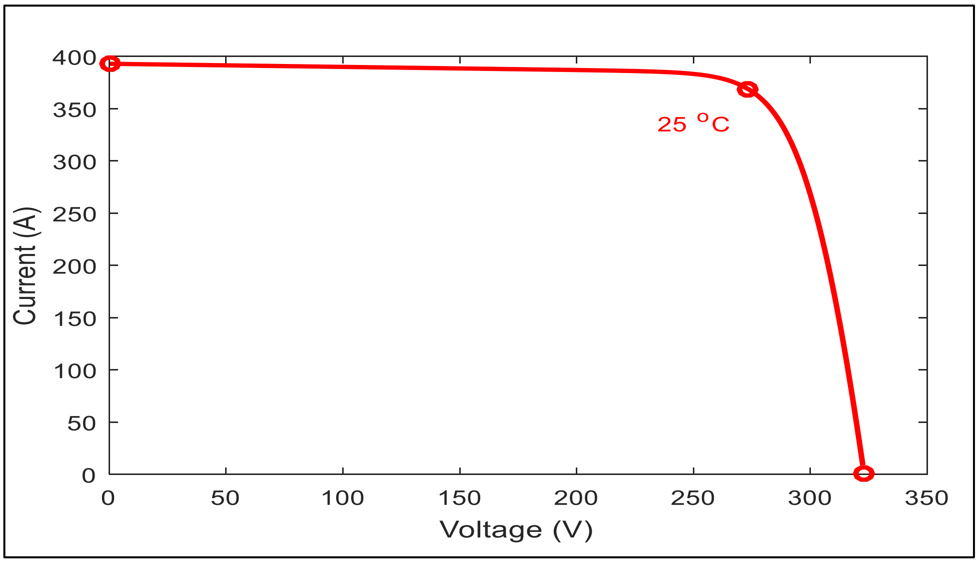

Figure III.3 Current-Voltage characteristics of a PV array fixed irradiation 1000W/m2 and temperature 25°C of SunPower SPR-315E-WHT-D array.

III-2-2 Boost converter characteristics

The DC/DC converter is used to transfer the power from the solar panel to the load side, ensuring maximum power transfer. Pulse width modulation (PWM) is used for this adjustment. The switching device is a MOSFET or IGBT. Maximum power is achieved by using an MPPT algorithm that adjusts the duty cycle of the converter.

Before the simulation, the first step is the determination of the parameters of the boost converter. The sizing of this converter, which is used for the tracking of the maximum power point, is different from the classical converter, where its input is typically fixed. The values of three parameters L, C1 and C2 are calculated using their formulas in the previous chapter. The specifications of the boost DC-DC converter are given in TABLE III-2:

Table III.2 Parameters of the boost converter.

Parameters	Values
Input inductance (L)	2.35mH
Input capacity (C1)	3.5mF
Output capacity (C2)	1mF
Load resistance (R)	10ohm
DC voltage, Vdc	12 V
Switching frequency	5000 Hz

III-3 PV array Maximum Power Point Tracking

System simulations using the various methods were carried out in the following sequence:

- As a function of fixed irradiation set at 1000 W/m² and fixed temperature 25°C for the MPPT IC (fixed and improved variable step size).
- As a function the variation of irradiation and fixed temperature 25°C for the MPPT IC algorithm (fixed and improved variable step size method).
- As a function the variation of irradiation and fixed temperature 25°C for the MPPT P&O algorithm (fixed and improved variable step size method).
- As a function the variation of irradiation and fixed temperature 25°C for the MPPT PID controller.
- The combination of the five techniques MPPT with the variation of irritation and fixed temperature 25°C.

The aim of these steps is to study the behavior of the various MPPT controls under fixed temperature and different irradiance conditions. The purpose of the simulation is to test the robustness of the controls.

III-3-1 Control of PV System with IC MPPT Methods

For the illustration to the efficiency of the improved variable step size IC MPPT method, a simulation and a comparative study between variable step size and fixed step size IC MPPT methods have been demonstrated.

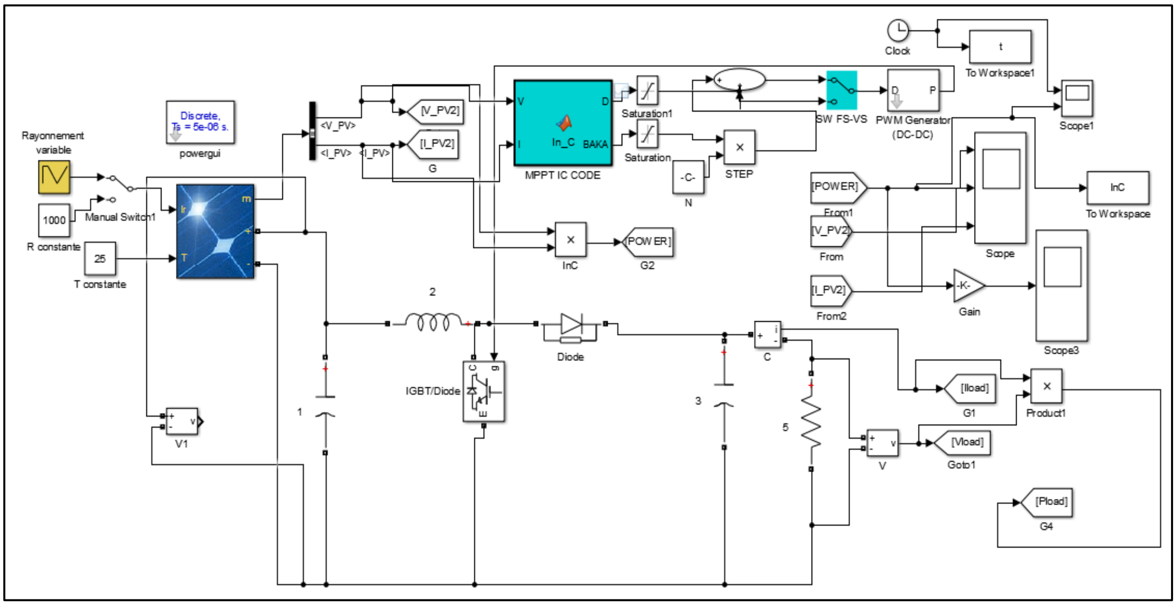

Figure III.4 Diagram block of IC MPPT method.

This figure illustrates the block diagram of the MPPT used with either a fixed or variable (switchable) radiation and fixed temperature panel. A boost converter is used as the DC/DC converter interface between the PV array and the load to obtain the MPP. the block MPPT code is the translation of the algorithm flowchart into C programming form, with the option of switching between fixed and variable steps. The scaling factor N is adjusted as 0.00005 (after many tests for a great adjustment).

The next figure shows the maximum power point tracking using both IC MPPTs in case of fixed irradiation level G=1000W/ m² and constant temperature T=25°C. The enlarged views of the Zoom A and Zoom B in Figure III.5. are shown in Figures III.6 and 7, respectively.

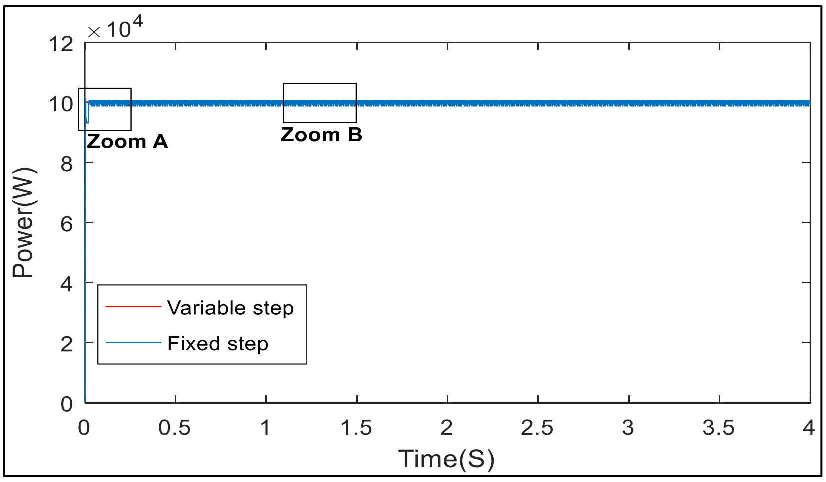

Figure III.5 PV array output power with fixed irradiation and temperature (G=1000W/m2 and T=25°C) in variable step size and fixed step size IC MPPT methods.

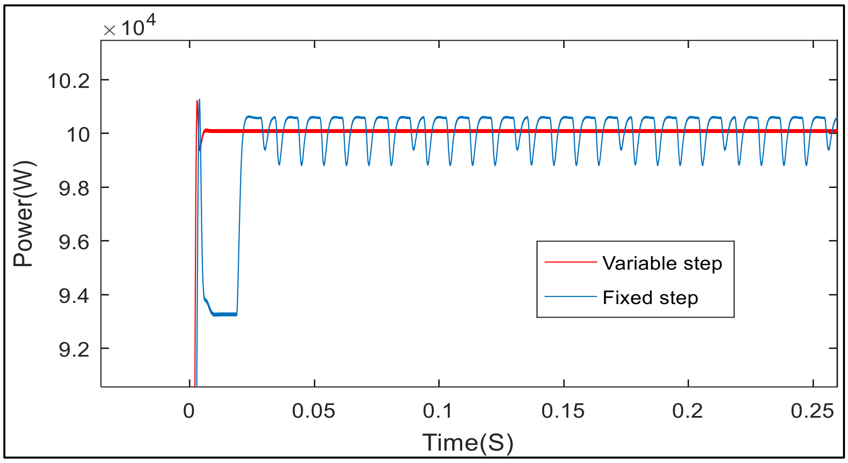

Figure III.6 Enlarged view of Zoom A.

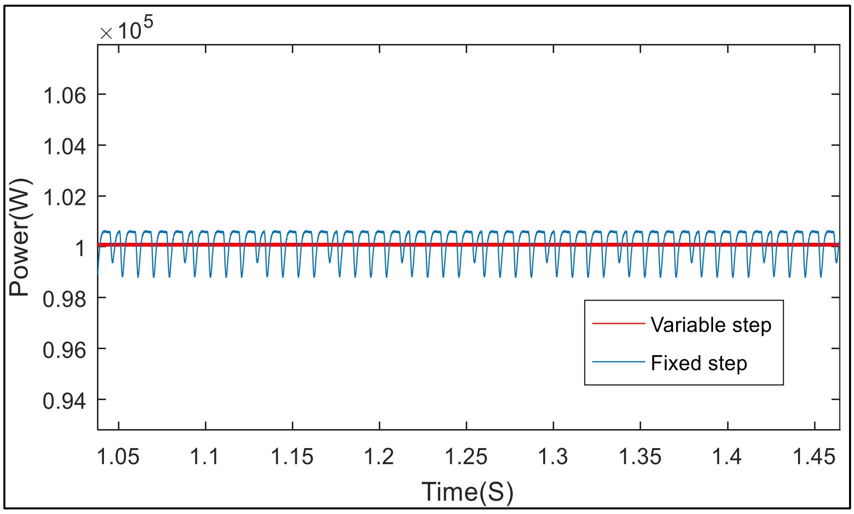

Figure III.7 Enlarged view of Zoom B.

As shown in Figure III.6, when the irradiance is 1000 W/ m², the conventional incremental conductance method enters a steady state at the 0.03 s; However, the improved incremental conductance method has entered a steady state at the 0.004 s, adjustment time is short, and the response speed is fast. In the steady state of Figure III.7, the output power of the traditional incremental conductance method oscillates greatly; The output power of the improved incremental conductance method also has no oscillation.

The MPP tracking using both IC MPPTs in case of changing irradiation level (T=25°C) from 1000 W/m² to 800 W/ m², from 800 W/ m² to 600 W/ m² and from 600 W/m² to 1000 W/ m². Figures III.8 and 9 show changing irradiation level with fixed step and variable step, the combination of these two figures is illustrated in figure III.10.

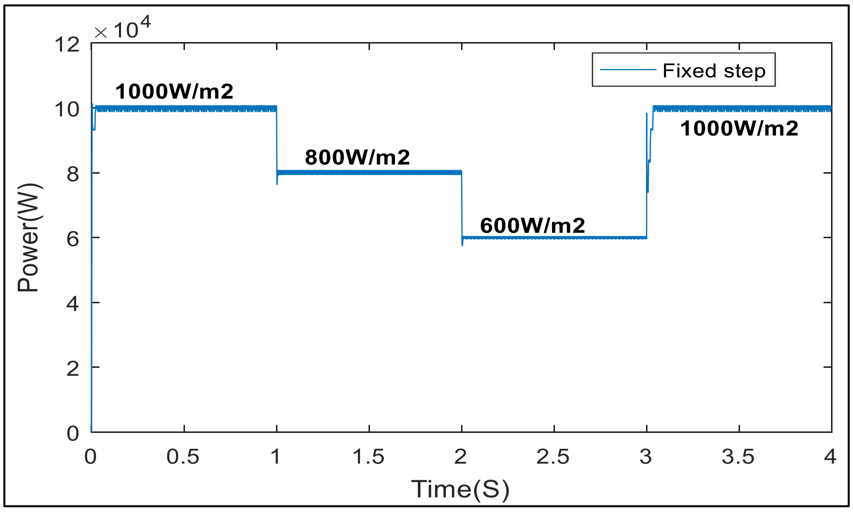

Figure III.8 PV array output power with variable irradiation on fixed step size IC MPPT method.

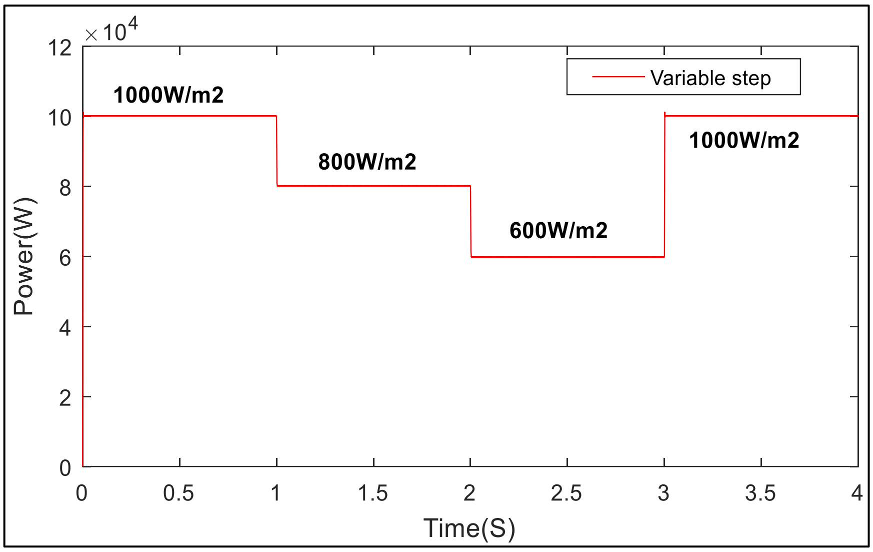

Figure III.9 PV array output power with variable irradiation on variable step size IC MPPT method.

The variable step minimized the oscillation, overshoot and response time of fixed step, figures III.11-13 show zooms for changing irradiation level from 1000 W/m m^2, from 800 W/ m^2 to 600 W/ m^2 and from 600 W/ m2 to 1000 W/ m^2.

From Figures III.5 to 13, it is clear that the variable step size IC MPPT performs better than the fixed step size IC MPPT in case of changing irradiation.

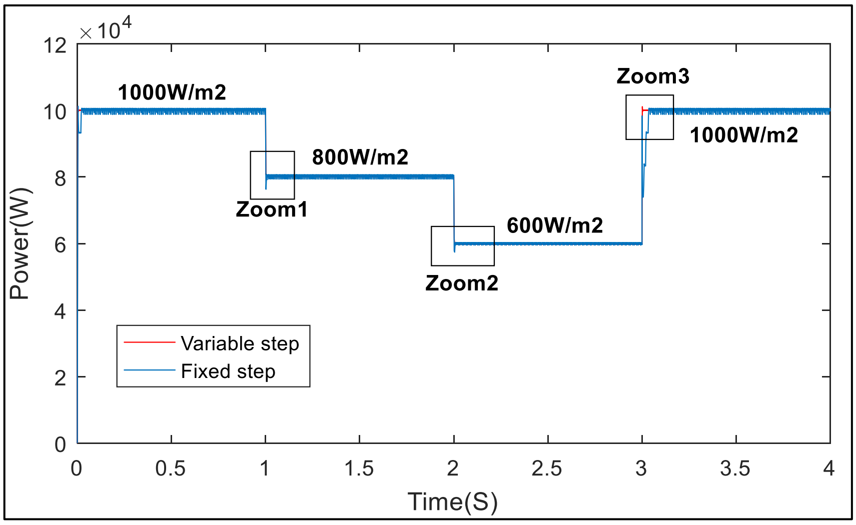

Figure III.10 PV array output power with variable irradiation on variable step size and fixed step size IC MPPT methods.

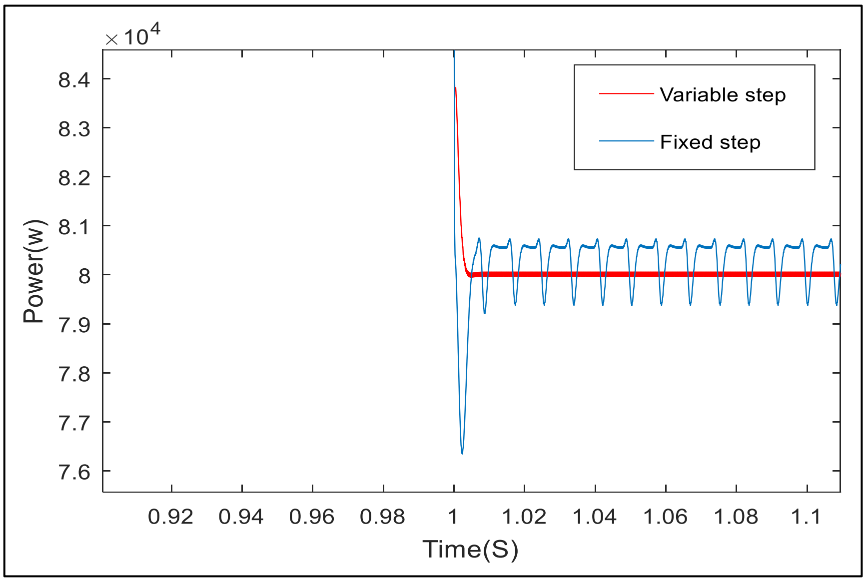

Figure III.11 PV array output power for irradiation descending: Zoom 1 in Point 800 W/ m2.

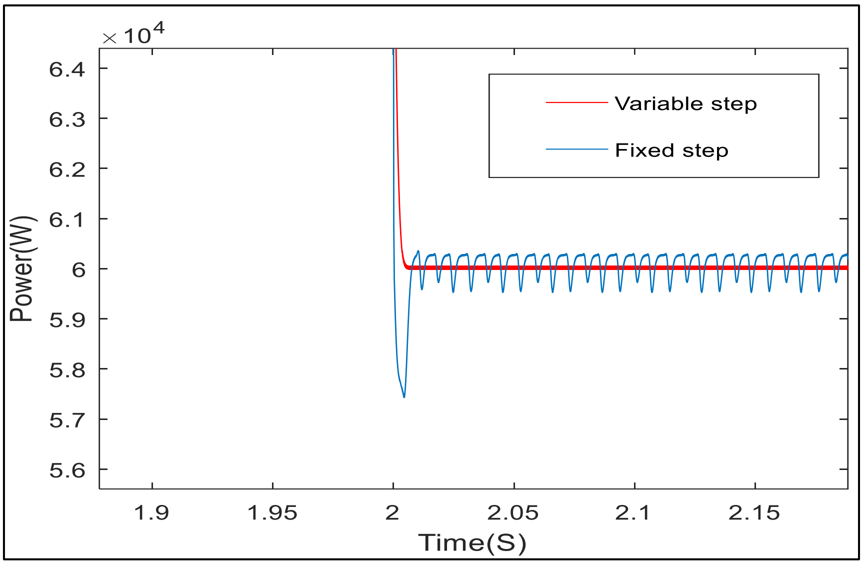

Figure III. 12 PV array output power for irradiation descending: Zoom 2 in Point 600 W/ m2.

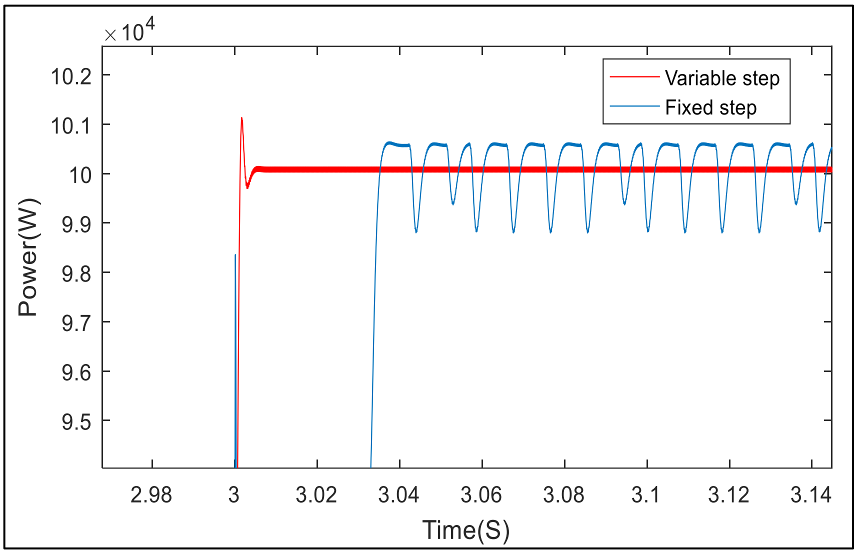

Figure III.13 PV array output power for irradiation ascending: Zoom 3 in Point 1000 W/ m2.

The simulation results show that the improved incremental conductance method has not only the potential to eliminate the oscillation phenomenon due to inappropriate step size adjustment, but also improve the efficiency of the photovoltaic power generation system (less energy losses), a good accuracy, faster converging speed, less oscillation around the MPP, no overshoot and no divergence from the MPP, while verifying the accuracy of the improved incremental conductance method, providing a reference for the MPPT control method under the change of irradiance.

III-3-2 Control of PV System with P&O MPPT Methods and PID Controller

a) P&O MPPT Methods

This algorithm has approximately the same diagram block as the IC algorithm MPPT Method but their difference is the flowchart, so in this case the MPPT code will not be the same and the scaling factor is equal to 0.001557 (after many tests for a great adjustment). The next figure shows the maximum power point tracking using both P&O MPPTs (conventional fixed step size and improved variable step size) in case of changing irradiation level (T=25°C) from 1000 W/m2 to 800 W/ m² and from 800 W/ m² to 600 W/ m² and from 600 W/m2 to 1000 W/ m².

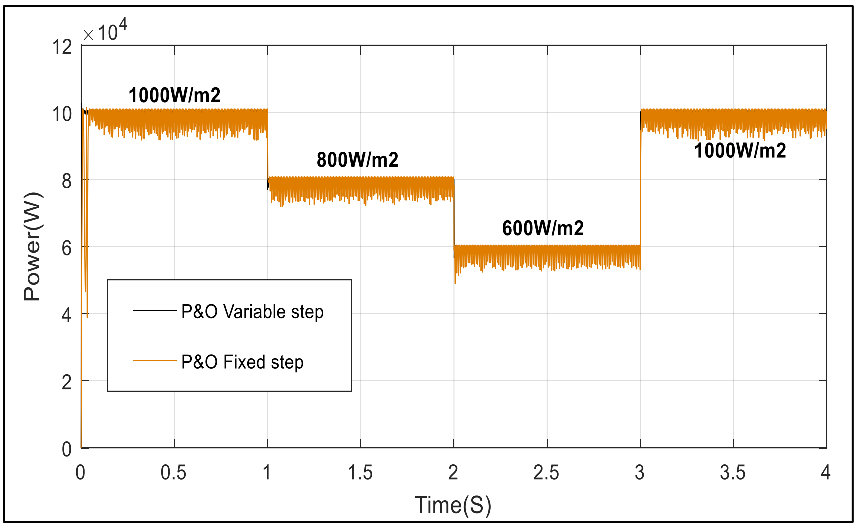

Figure III.14 PV array output power with variable irradiation on variable step size and fixed step size P&O MPPT methods.

As shown in Figure III.14, the output power of the traditional method oscillates greatly; The output power of the improved variable step method also has less oscillation in steady state. The enlarged views of any point will be clearly shown in the case of combination of the five techniques.

b) PID Controller Method

The PID controller controls the error between the Photovoltaic Generator output voltage and the reference voltage, which helps to reduce power consumption. the gain values P, I and D equal to 0.2, 2 and 0 respectively (after many tests for a great adjustment). For finding the gains values, we have two methods: the closed loop and test in this case we used the second method. The Figures III.15 and 16 show the diagram block of the PID Controller MPPT Method and the diagram block of the equation reference voltage respectively.

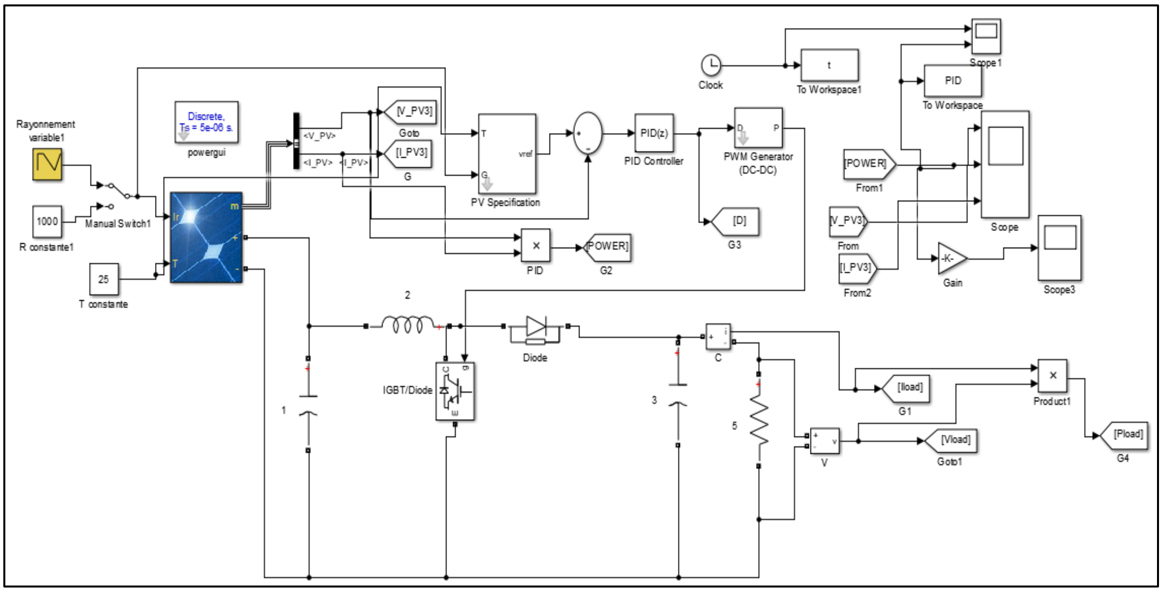

Figure III.15 Diagram block of the PID Controller MPPT Method.

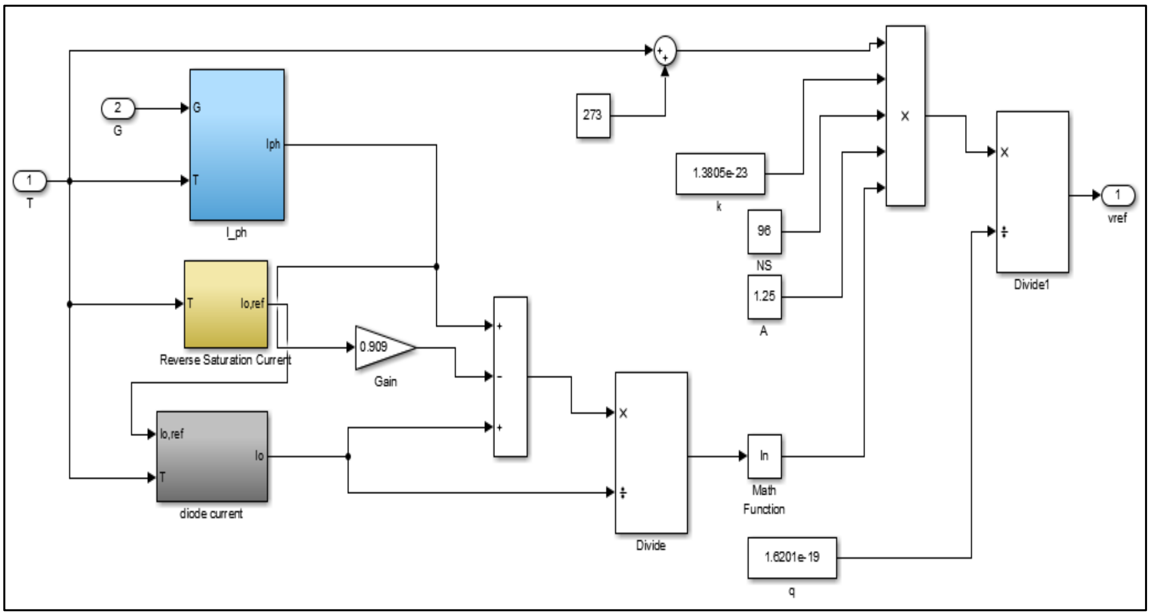

Figure III.16 Block of the reference voltage.

The next figure shows the maximum power point tracking using PID Controller MPPT method in case of changing irradiation level (T=25°C) from 1000 W/m2 to 800 W/ m², from 800 W/ m² to 600 W/ m² and from 600 W/m2 to 1000 W/ m². The PID Controller MPPT method has no oscillation and overshoot, so it doesn't have a variable step size and it's be demonstrated in this concerned figure.

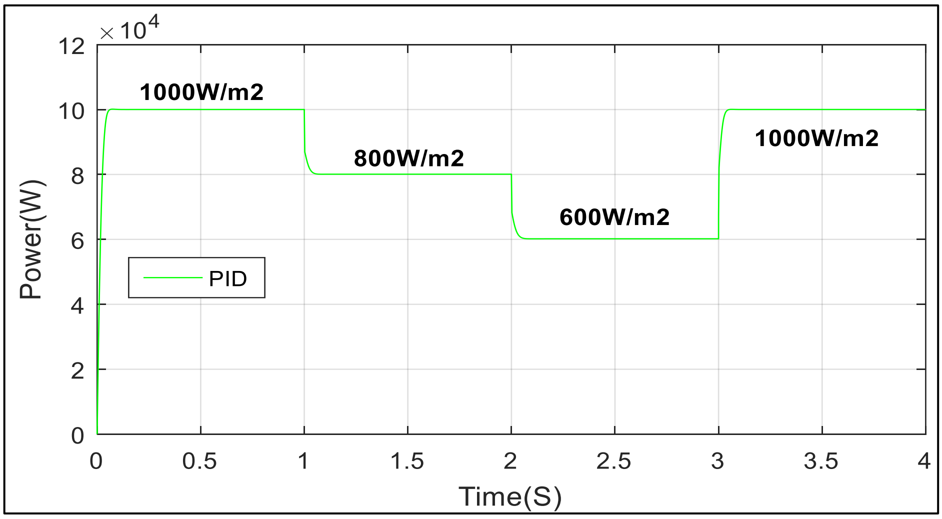

Figure III.17 PV array output power with variable irradiation of the PID Controller MPPT method.

III-3-3 Comparative study between five MPPT techniques

The combination of these previous five techniques is illustrated in Figure III.18, Five MPPT methods will be analyzed and compared the first is the Perturb and Observe (P&O) with fixed step size, the second P&O with variable step size, the third is the Incremental Conductance (IC) with fixed step size, the fourth IC with variable step size and the fifth is the Proportional Integral and Derivative (PID) Controller.

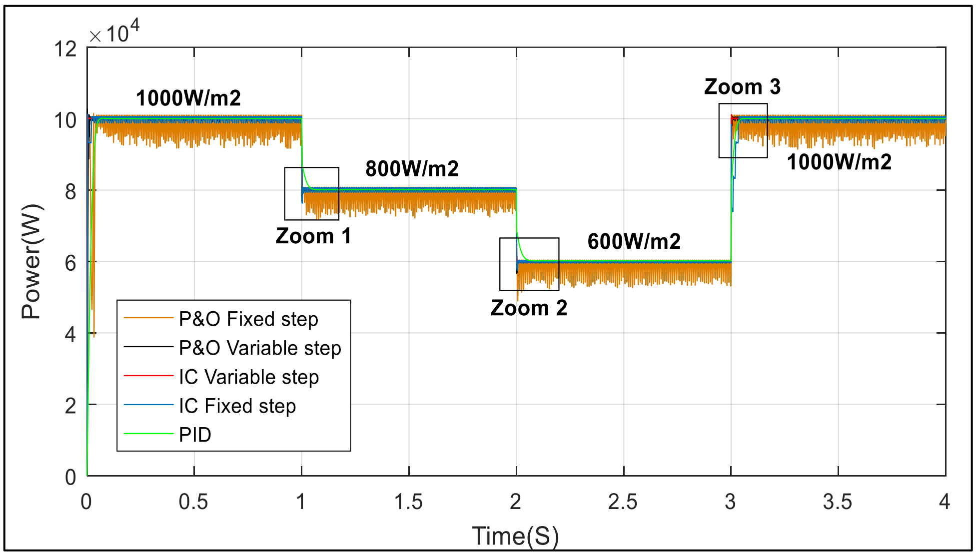

Figure III.18 Panel power with different MPPT methods.

The variable step minimized the oscillation, overshoot and response time of fixed step, figures III.19-21 show clearly zooms for every changing irradiation level from 1000 W/ m2 to 800 W/ m2, from 800 W/ m2 to 600 W/ m2 and 600 W/ m2 to 1000 W/ m2 respectively. The next tables will analyze and compare these MPPT methods according some important performances: the oscillations, overshoot, response time and energy losses.

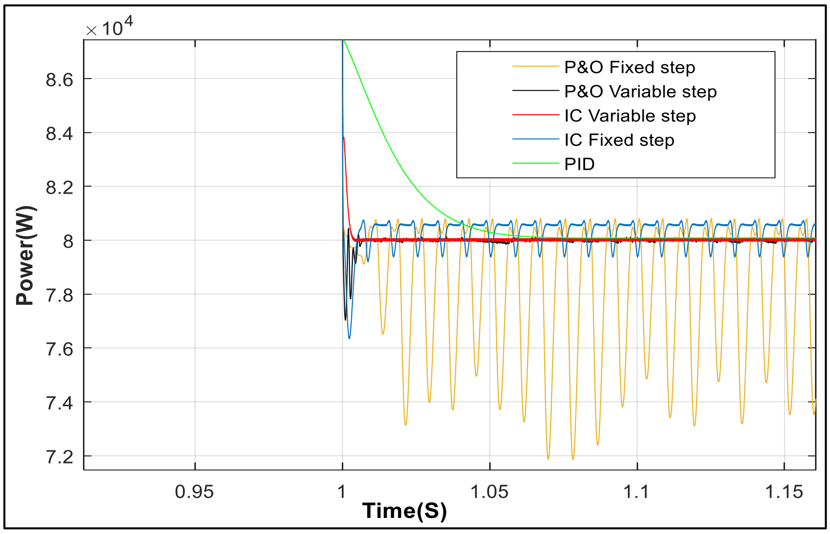

Figure III.19 PV array output power for irradiation descending: Zoom 1 in Point 800 W/ m2.

Table III.3 Performance comparison for varying irradiation (decrease) from 1000 W/ m2 to 800 W/ m2.

Performance Index	P&O		IC		PID
	Fixed step	Variable step	Fixed step	Variable step	
Oscillations	1.25	0.02	0.13	0.0082	0
Overshoot	1.1	0.3	0.36	0.0001	0
Response time	1.014	1.007	1.006	1.003	1.02

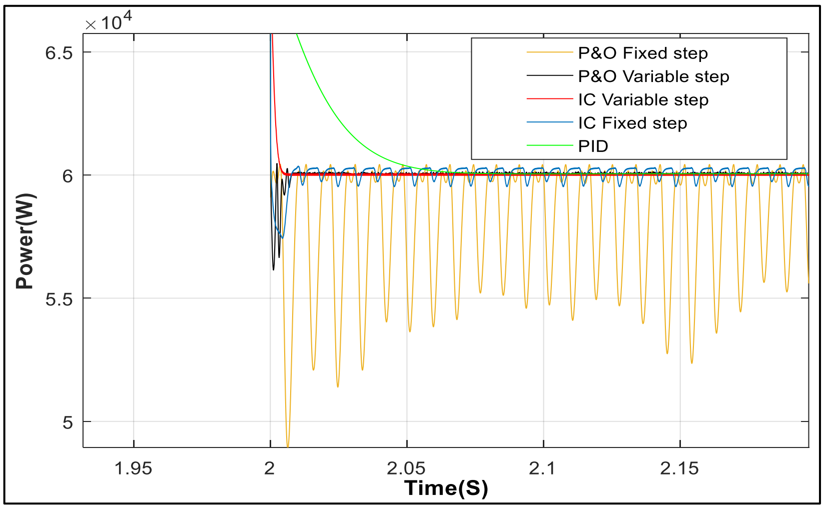

Figure III.20 PV array output power for irradiation descending: Zoom 2 in Point 600 W/ m2.

Table III.4 Performance comparison for varying irradiation (decrease) from 800W/ m2 to 600 W/ m2.

Performance Index	P&O		IC		PID
	Fixed step	Variable step	Fixed step	Variable step	
Oscillations	0.95	0.012	0.1	0.008	0
Overshoot	1.3	0.35	0.25	0.0001	0
Response time	2.007	2.001	2.004	2.0039	2.04

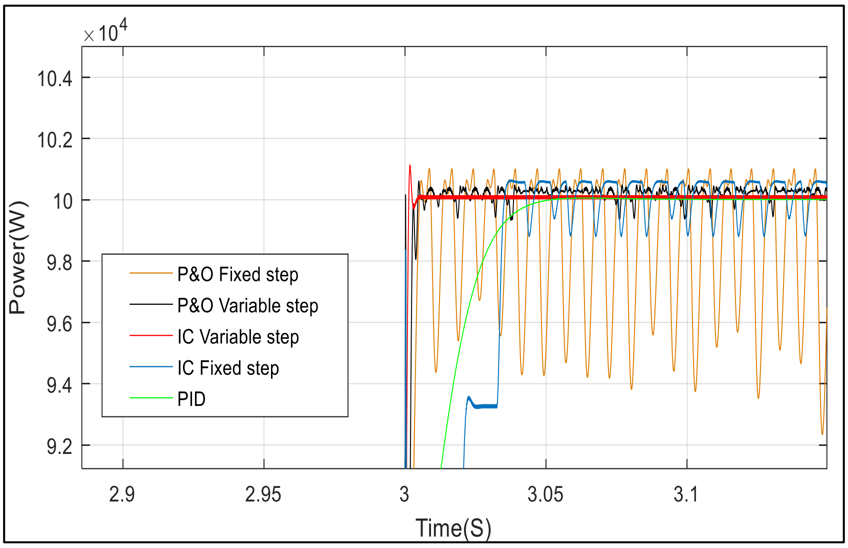

Figure III.21 PV array output power for irradiation ascending: Zoom 3 in Point 1000 W/ m2.

Table III.5 Performance comparison for varying irradiation (increase) from 600 w/ m2 to 10000 w m2.

Performance Index	P&O		IC		PID
	Fixed step	Variable step	Fixed step	Variable step	
Oscillations	0.9	0.11	0.26	0.008	0
Overshoot	1.4	0.2	0.65	0.03	0
Response time	3.018	3.0036	3.03	3.003	3.04

The **P&O** algorithm is highly dependent on the initial conditions and shows important oscillations around the optimal value. The main disadvantage of this algorithm is its poor behavior after a sudden change in irradiance but this proposed variable step size improved the fixed step performances. The **IC** algorithm appears to be an improvement on the P&O algorithm. In fact, it performs better in rapidly changing weather conditions, his variable step size shows good behavior and performance in terms of accuracy, efficiency, minimization of the oscillations, ripple, overshoot and the loss of power in each change. The **PID** Controller requires the specifications of the PV array or panel, except for the slow response time and energy losses it also have a good performance. The most disadvantage of PID Controller are the optimization of PID gains, which we must recalculate them for each specific condition (load and panel).

Conclusion

In this chapter, the simulations were conducted in the MATLAB/SIMULINK and the results were obtained for the strategy control applied to PV System using different MPPT techniques to extract the maximum power from the PV generator. The main focus is the simulation of an improved variable step size with the incremental conductance algorithm. Then, for the credibility of this technique the second part of the system is a comparison between this technique, his conventional technique and other algorithms (P&O (fixed and variable step size) and PID Controller) with simulation and table of comparison according different performances under the changing of irradiances (descending and ascending) and fixed temperature 25°C. Finally, we can conclude the IC technique with the improved variable step size is better than other techniques used in this study according different performances.

GENERAL CONCLUSION

General Conclusion

Renewable energies are currently a major focus of scientific research because they offer an alternative to polluting fossil fuels. Solar energy is promising because it is inexhaustible, and its use can be a cost-effective, environmentally friendly solution to meeting people's energy needs. Photovoltaic energy involves the conversion of sunlight into electricity using photovoltaic panels. Although it is an abundant, non-polluting form of energy, it has low efficiency and high initial investment costs, though operating and maintenance costs are low.

The objective is to ensure, improve and maximize the energy produced by the photovoltaic field through an optimal design and a dynamic control strategy leading to an overall improvement in the efficiency of the electrical conversion system. An MPPT controller forces the generator to operate at its maximum power point (MPP). This ensures the photovoltaic field's maximum power efficiency, regardless of weather conditions. We have studied the implementation and simulation of various MPPT methods and their relatively simple programming algorithms in the MATLAB/SIMULINK environment.

This enabled the validation of simulations of conventional and improved methods operating under different irradiance and fixed temperature conditions. The characteristic curve of the PV system is nonlinear, and the amount of power extracted varies according to different climatic conditions. The power produced by the PV panel is directly proportional to irradiance and inversely proportional to temperature. There is a maximum operating point for each irradiance and temperature value. The DC-DC converter with the MPPT algorithm is an important component of the PV system. It achieves maximum power transfer between the source and load and improves system efficiency.

It should be noted that conventional maximum power point tracking (MPPT) methods with a fixed step size (P&O and IC) generate oscillations proportional to the chosen step size around the maximum power point (MPP). Their response time is inversely proportional to the step size. Improved MPPT methods with a variable step size (P&O and IC) perform better than previous methods, with smaller oscillations and a faster response time. The same is also observed with the MPPT PID Controller method, compared to the other techniques studied. The variable step size IC MPPT technique results in less significant oscillations and better efficiency. However, the PID controller technique minimizes oscillations but has a slow response time, resulting in energy loss.

The potential perspectives for the extension of this work are:

- Experimental validation of the MPPT methods presented;
- Using hybrid control to improve the performance of MPPT algorithms;

- The control of PV System using a single sensor in case one of sensor is defective;
- Consideration of other constraints (shading, optimal position…);
- Management of a photovoltaic system connected to a grid;
- The optimization using ANOVA and Taguchi method.

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