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***Simulation and Realization of MPPT methods
in photovoltaic system***

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الملخص:

تكتسب الطاقة الكهروضوئية (PV) مكانتها بشكل متزايد في مصادر الطاقة البديلة ، لكن الألواح الشمسية ، على الرغم من التطور في تقنيات التصنيع ، تعاني من كفاءة تحويل طاقة منخفضة إلى حد ما ، ويمكن أن تكون هذه الكفاءة أقل إذا لم يعمل المولد الكهروضوئي (PVG) حول نقطة تسمى: نقطة الطاقة القصوى MPP. يعد السعي وراء هذه النقطة ، التي تغير الموقع مع الظروف المناخية ، خطوة مهمة للغاية في تصميم نظام الكهروضوئية. سنتقوم في هذه الأطروحة بمحاكاة وتحسين وتحقيق نظام فلتائي ضوئي يعمل بمحول معزز. تغطي هذه الدراسة تنفيذ خوارزميات مختلفة لأقصى نقطة للطاقة مثل خوارزمية الاضطراب والمراقبة (P&O) ، والتوصيل الإضافي (Inc) ، والمنطق الضبابي و PSO-PID ، لذلك سنبدأ بمحاكاة ونمذجة الخلية الضوئية ومحول التعزيز وفقاً للنموذج الرياضي. بعد ذلك ، قمنا بتفصيل العديد من خوارزميات MPPT التي تتحكم في المحول الخاص بنا. أخيراً ، لدينا تصميم وتنفيذ نظامنا باستخدام خوارزميتين MPPT استناداً إلى لوحة Arduino Mega 2560.

الأعمال الأساسية: مولد الطاقة الكهروضوئية ، MPP ، الداعم ، P&O ، INC ، المنطق الضبابي ، PSO-PID ، المحاكاة ، التنفيذ ، MPPT ، Arduino Mega.

Abstract:

Photovoltaic energy (PV) is increasingly gaining its place in alternative energy sources but solar panels, despite the development in manufacturing technologies, suffer from a fairly low energy conversion efficiency, this efficiency can be even lower if the photovoltaic generator (PVG) does not work around a point called: maximum power point MPP. The pursuit of this point, which changes position with climatic conditions, is a very important step in the design of a PV system. In this thesis we are going to simulation, optimization and realization of a photovoltaic system operating with a booster converter. This study covers the implementation of different algorithms of the maximum power point such as by the perturbation and observation algorithm (P&O), Incremental conductance (InC) , Fuzzy logic and PSO-PID .Therefore, we will start with the simulation and modeling of the photovoltaic cell and the boost converter according to the mathematical model. Then, we have detailed several MPPT algorithms controlling our converter. Finally, we have design and implementation of our system with the two MPPT algorithms based on an Arduino Mega 2560 board.

Keywords: Photovoltaic generator, MPP, booster, P&O, INC, Fuzzy logic, PSO-PID, Simulation, Implementation , MPPT, Arduino Mega.

Résumé :

L'énergie photovoltaïque (PV) gagne de plus en plus sa place dans les sources d'énergie alternatives mais les panneaux solaires, malgré le développement des technologies de fabrication, souffrent d'un rendement de conversion énergétique assez faible, ce rendement peut être encore plus faible si le générateur photovoltaïque (PVG) ne fonctionne pas autour d'un point appelé : point de puissance maximale MPP. La poursuite de ce point, qui change de position avec les conditions climatiques, est une étape très importante dans la conception d'un système PV. Dans cette thèse nous allons simuler, optimiser et réaliser un système photovoltaïque fonctionnant avec un survolteur. Cette étude couvre la mise en œuvre de différents algorithmes du point de puissance maximale tels que l'algorithme de perturbation et d'observation (P&O), la conductance incrémentale (Inc), la logique floue et le PSO-PID. Par conséquent, nous commencerons par la simulation et la modélisation du cellule photovoltaïque et le convertisseur boost selon le modèle mathématique. Ensuite, nous avons détaillé plusieurs algorithmes MPPT contrôlant notre convertisseur. Enfin, nous avons conçu et mis en œuvre notre système avec les deux algorithmes MPPT basés sur une carte Arduino Mega 2560.

Mots clés : Générateur photovoltaïque, MPP, booster, P&O, INC, Logique floue, PSO-PID, Simulation, Implémentation, MPPT, Arduino Mega.

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List of symbols and abbreviations

PV: Photovoltaic.

PVG: Photovoltaic generator.

MPPT: Maximum Power Point tracking.

KVL : Kirchhoff's Voltage Law

P&O: Perturbation and observation method.

InC :Incremental conductance method.

FLC: Fuzzy Logic Controller.

VOC : 5 Fractional open circuit voltage.

PID : Proportional-Integral-Derivative.

PSO : particle swarm optimization

E: Illumination (W/m^2).

I_{ph} : The photo-current (A).

I : The current generated by the solar cell (A).

I_s : The saturation current (A).

I_{sc}: the short-circuit current (A).

I_L : The chopper inductance current (A).

I_{pv} : Current delivered by the PV generator (A).

V : the voltage across the cell (V).

q : The charge of the electron = $1,6 \cdot 10^{-19}$ C.

R_s : Series resistance (Ω).

R_{sh} : The shunt resistors (Ω).

T : The operating temperature in Kelvin.

A : the quality factor of the cell

V_{th}: Thermal tension.

V_{oc} : The open circuit voltage (V).

P : Characteristic power (W).

P_{max} : The maximum power (W).

FF : Form factor.

N_s : Number of modules in the panel in series.

N_p : Number of modules in the panel in parallel.

V_{opt} : Optimal tension(V)

I_{opt} : Optimum current (A).

General Introduction

Renewable energies and in particular photovoltaic energy have become very promising sources in the future energy resources of a country, first of all because of its own nature, but also because of the decrease in the reserves of conventional resources (oil, gas, etc ...), the demographic and economic growth of this country, encouraging the production of more electrical energy [3].

Several renewable energy resources have been discovered in recent years, including wind, hydro and photovoltaic energy, the latter being one of the most renewable energies in the world. [3], [4]

Photovoltaic energy is obtained directly from the sun's radiation. It can even be transformed into electrical energy thanks to the photovoltaic effect. Photovoltaic panels made up of photovoltaic cells have the ability to transform photons into electrons. Energy in the form of direct current is thus directly usable.

The efficiency of photovoltaic systems can be improved by solutions using techniques for finding the maximum power point (known as MPPT techniques). [5]

In this thesis, we are mainly interested in the development of an optimization procedure which allows the point tracking of the maximum power (Maximum Power Point Tracking MPPT) of a photovoltaic generator (GPV), for a good exploitation of the generator. photovoltaic. This requires the implementation of a maximum power point tracking technique, such as the Perturbation-Observation (P&O) method and the Fuzzy approach. Thus, we present in this project the simulation under matlab/simulink and the realization of a digital MPPT control based on two MPPT algorithms which are P&O, INC, by making a realization by means of 'an Arduino Mega 2560 board with an MPPT control.

The thesis consists of three chapters:

In the first chapter we will present a generality on photovoltaic systems. By presenting the photovoltaic generator and the principle of photovoltaic conversion, then the modeling of the photovoltaic module.

In the second chapter, we started with MPPT Problem and why we need mppt in our system then we studied DC-DC converter commonly used in photovoltaic systems (the Boost converter) then we studied modeling and the operating principle.

The third chapter is devoted to the principle of search in PPM, we have introduced many mppt algorithms and explained the principle of each of them and In the last chapter we will present the results of simulation and experimental tests

Finally, we will end our thesis with a general conclusion that will summarize the interest of our study.

CHAPTER I

Generalities on Photovoltaic Systems

Chapter I

Generalities on Photovoltaic Systems

I.1 Introduction :

The various sources of energy available in the world, apart from nuclear and geothermal energies, are all of solar origin. Indeed, even coal and oil come from plants, which depend on the sun. Nature therefore transforms solar energy into many other sources, but never into electricity. To reach this stage, man is obliged to apply additional transformations to these sources which will reduce the overall energy conversion efficiency. In what follows, we will first focus on the different energy sources existing in the world, specifying photovoltaics as a method of direct conversion of solar photons into electricity.

During the last decades, the world consumption of energy has increased considerably, this increase is due to the increase of the world population on the one hand and the explosion of the industrial development of the industrialized countries. Currently the production of energy is based on non-renewable energies namely petroleum, natural gas, coal and uranium (figure 1.1) [1]. Following the increase in the rate of global energy consumption, Plus the two serious problems posed by these energies: on the ecological level (pollution and global warming) and on the political level between countries (conflicts between states to order fossil fuel reserves), these sources are exhaustible. Thus man will be condemned to find other sources to meet the energy needs of future generations. So-called renewable energies are the best solution to overcome these problems. The production of these energies is based on forces or resources whose stocks are unlimited.

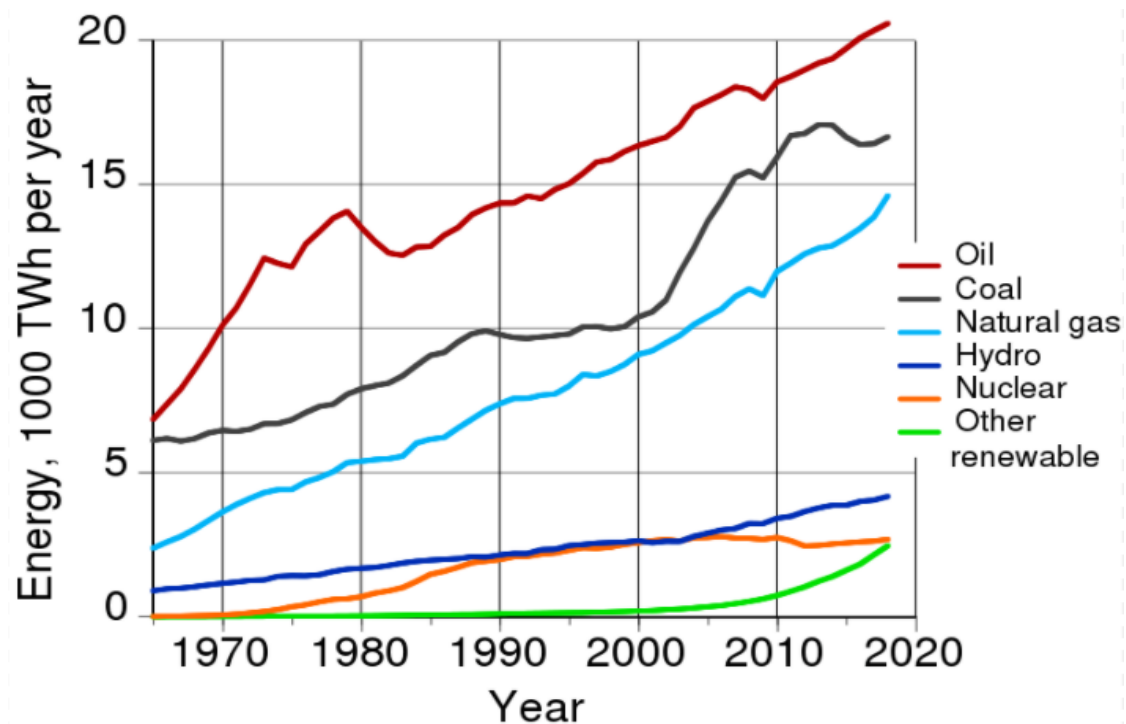


Figure I. 1:Evolution of global electricity consumption.

There are several types of renewable energies namely: geothermal energy comes from the heat of the depths of the earth. Hydroelectric power, wind power, biomass power and solar power. These types of energy come directly or indirectly from the sun [1].

I.2 Solar energy:

The sun is an almost inexhaustible source of energy that sends radiation to the earth's surface which is approximately 8,400 times the energy consumption of humanity each year. This corresponds to an instantaneous power received of $1\text{kWp} / \text{m}^2$ distributed over the entire spectrum, from ultraviolet to infrared. The deserts of our planet receive in 6 hours more energy from the sun than mankind consumes in a year.

Solar energy is produced and used in several ways:

- Solar thermal energy: which simply consists of producing heat using dark panels. You can also produce with steam from the heat of the sun and then convert the steam into electricity.
- Photovoltaic solar energy: which consists of producing electricity directly from light using solar panels. This form of energy is already exploited in many

countries, especially in countries or regions that do not have conventional energy resources such as hydrocarbons or coal.

- passive solar energy: is another form of solar energy use which consists of using light directly for heating [2].

I.3 Evaluation de l'énergie renouvelable en Algérie :

The Algeria initiates a dynamic green energy by launching an ambitious program of development of renewable energy and energy efficiency. This vision of the Algerian government relies on a strategy focused on the development of inexhaustible resources such as solar and using them to diversify energy sources and prepare for the Algeria of tomorrow.

The program adopted in 2011 for an overall objective consists in the installation of 22,000 MW by 2030, of which 10,000 MW could be dedicated to export[4].

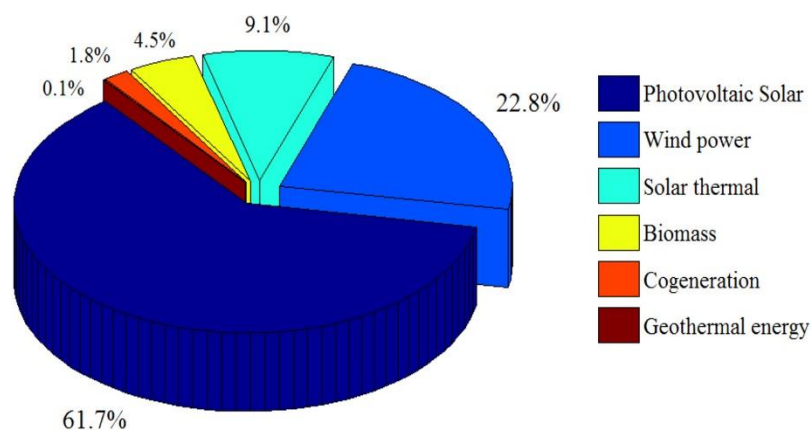


Figure I. 3: Distribution of development program of renewable energy technology sector.

I.3.1 Potentiel solaire :

In all Mediterranean basins, there is a gigantic reservoir of solar energy in the north of Africa and particularly the southern region of Algeria. The potential of this type of energy in southern Algeria is the largest .

The sunshine duration of almost all the national territory exceeds 2000 h annually and reaches 3900 h (high plains and Sahara). The energy received daily on a horizontal surface of 1 m² is about 5 Kwh over most of the country, or nearly 1700 kWh/m²/year in the north and 2263 kWh/m²/year in the south[3].

Region	Coastal	Highlands	Sahara
Area (%)	4	10	86
Average sun hours per year	2650	3000	3500
Energy received KWh/m ² /year	1700	1900	2650

Table I. 1: Data on solar radiation in Algeria.

I.4 Solar Energy and the Photovoltaic Effect:

Electricity is one of the most versatile forms of energy, and it best adapts to every need. Its use is so extensive, that today it would be difficult to design a technically advanced society that doesn't make use of it. Thousands of devices are designed to run on electrical energy, either in the form of low voltage direct current or higher voltage alternating current. It is very interesting to produce electricity with a safe and non-polluting source of energy, such as solar energy.

There are two methods to be able to convert solar energy into electricity, depending on whether kinetic energy is used as an intermediate form of the conversion process:

- Thermodynamic conversion systems.
- Direct systems, based on the physical interactions between the photons of the incident radiation and the electrons of the material, the photovoltaic effect.

I.4.1 Principle of the Photovoltaic Effect:

It is the conversion of the energy carried by photons of light when they collide with suitably processed semiconductor materials into electrical energy capable of creating a current of electrons through an external circuit. The key to producing a useful electric current is to extract the electrons that are released.

One method of doing this is to introduce chemical elements into the semiconductor material that help to produce excess electrons and holes. These elements, which significantly alter the intrinsic properties of the semiconductor, are called dopants and the material is said to be doped when the process of incorporation into the semiconductor is completed.

A suitable dopant for silicon is boron. The structure created is called a P-type (positive) semiconductor. Another possible dopant for silicon is phosphorus. The semiconductor is said to be of type N (negative). If the photons of the incident light impart energy to the electrons in the semiconductor, some electrons can cross the potential barrier, being expelled out of the semiconductor into an external circuit. This generates an electric current. The electrons, after having traversed the external circuit, return in the semiconductor by the opposite face.

The semiconductor material therefore does not store electrical energy but generates it by transforming the incident energy. Quantum physics predicts a theoretical yield for the silicon cell of 26% but commercial cells obtained industrially do not rise above 17%. These values, implying a limitation on the electric power obtainable, show that only a small part of the solar energy can generate electricity.

I.4.2 Solar Cell and Modeling:

Figure (I.3) shows the cross section of a typical PV cell:

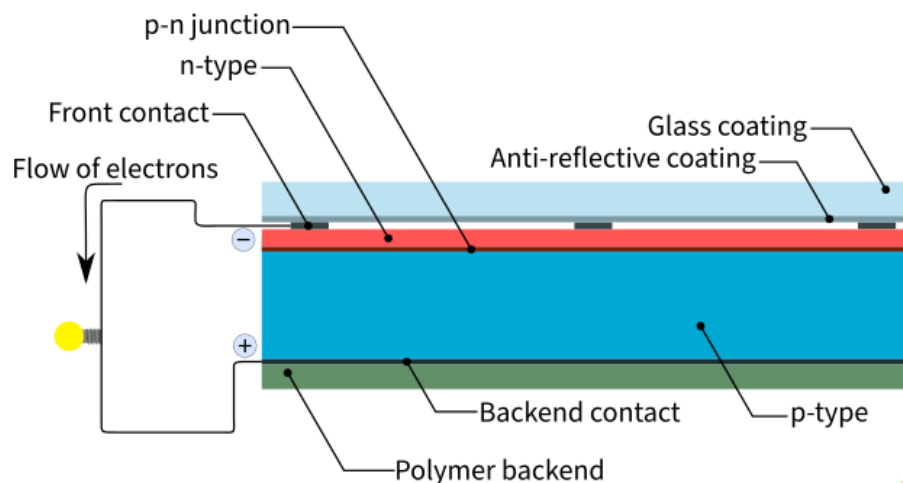


Figure I. 5: Cross section of a typical PV cell.

The photovoltaic cell is formed by a semiconductor material of the P-N type. The size of each cell ranges from a few square centimeters up to 100 cm² or more. Its shape is circular, square or derived from the two geometries.

The maximum cell voltage is around 0.6V for zero current. This voltage is called the open circuit voltage(V_{oc}). The maximum current occurs when the terminals of the cell are short-circuited, it is called short-circuit current (I_{sc}) and is highly dependent on the level of illumination. A PV cell has, as we see in figure (I.4), a nonlinear characteristic $I = f(v)$

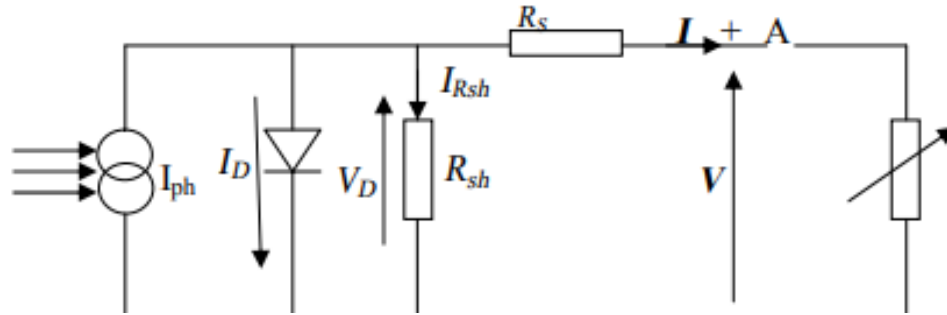


Figure I. 7:Equivalent diagram of a solar cell.

And

therefore , a PV cell made up of a silicon-based PN junction can be modeled by the following equation:

$$I = I_{ph} - I_D - I_{sh} \dots \dots \dots (1.1)$$

$$I = I_{ph} - I_S \left[\exp \left(q \frac{V + R_S I}{AKT} \right) - 1 \right] - \frac{V + R_S I}{R_{Sh}} \dots \dots \dots (1.2)$$

$$V_{th} = \frac{AKT}{q} \dots \dots \dots (1.3)$$

Where:

I_{ph} : The photo-current. q : The charge of the electron = $1.6 \cdot 10^{-19}$ C.

I : The current generated by the solar cell. A : The quality factor of the cell.

V : The voltage at the terminals of the cell. K : the boltzmanne constant = $1.38 \cdot 10^{-23}$ J / K

R_s : The series resistance. T : The operating temperature in Kelvin.

R_{sh} : The shunt resistance. V_{th} : Thermal tension.

I_S : The saturation current.

Five parameters must be evaluated, whatever the lighting and temperature conditions, they are: R_s ; I_S ; R_{sh} ; I_{ph} ; V_{th} .

We can determine them namely:

- the open circuit voltage V_{oc} ,
- the short-circuit current I_{sc} ,
- the characteristic power P_p ,
- the maximum power, P_{max} ,
- the form factor FF , and the efficiency.

Brief definitions of these parameters, as well as their characteristic determinations are given below [1].

The quality factor of cell A depends on the recombination mechanisms; it is equal to 2 for crystalline cells and between 1 and 2 for amorphous cells. It is close to 1 for high currents and increases to 2 for low currents [5].

The resistance R_{sh} comes from losses by recombination mainly due to thickness, surface effects, as well as the non-ideality of the junction. In practice, this resistance is very large compared to the series resistance (the order of the mega Ohm), its effect is neglected. This results in a simplified equivalent electrical circuit as shown in the figure below:

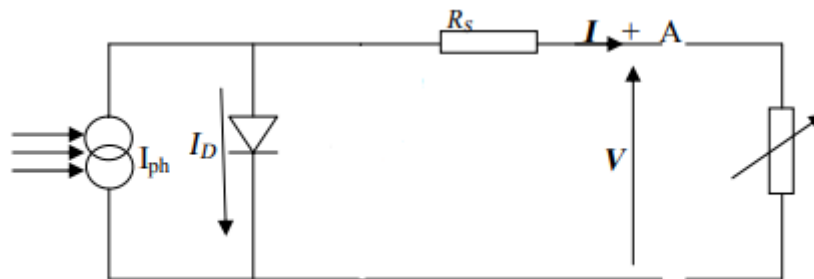


Figure I. 9:simplified equivalent diagram of a real solar cell connected to a load .

And its original equation (1.2) then becomes:

$$I = I_{ph} - I_S \left[\exp \left(q \frac{V + R_s I}{A K T} \right) - 1 \right] \dots \dots \dots (1.4)$$

a PV cell has, as we see in figure (1.6), a characteristic $I = f(V)$ and, $P = f(V)$ non-linear. The use of the electrical model of the PV cell allows to simulate its behavior in the MATLAB environment of Mathworks

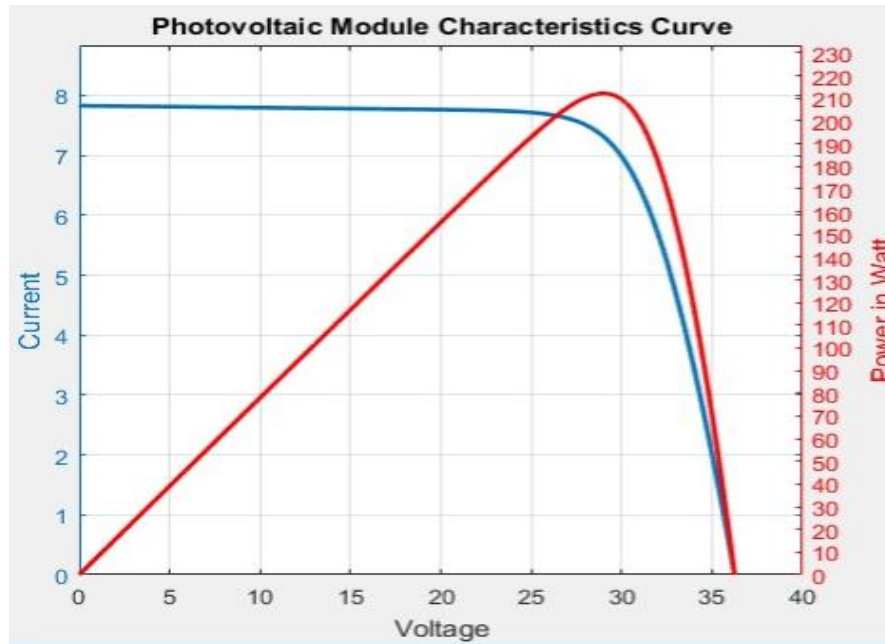


Figure I. 10:Characteristic U-I and P-V of a photovoltaic cell.

a) The series resistance R_s :

The series resistance R_s represents the various contact and connection resistances, it mainly due to losses by Joule effects through the collection gates and the inherent resistance of semiconductors, as well as to bad contacts (semiconductor, electrodes) . It plays an important role on the slope of the curve (I-V) in open circuit, In practice, the series resistance R_s is very low (on the order of a few milli-ohms). It has as a relation:

$$R_s = -\left. \frac{dV}{dI} \right|_{V_{OC,0}} - \frac{1}{X_V} \dots \dots \dots (1.5)$$

$$X_V = \frac{I_{s,0}}{V_{th,0}} e^{\frac{V_{OC,0}}{V_{th,0}}} \dots \dots \dots (1.6)$$

b) The saturation current I_s :

The saturation current I_s of the diode at a temperature T_0 is given by:

$$I_{s,0} = \frac{I_{SC,0}}{(e^{V_{OC,0}/V_{th,0}} - 1)} \dots \dots \dots (1.7)$$

it depends on the temperature. Its value for a given temperature is calculated by the following equation:

$$I_s = I_{s,0} \cdot \left(\frac{T}{T_0} \right)^{\frac{3}{n}} \cdot e^{-\frac{qV_g}{nk} \left(\frac{1}{T} - \frac{1}{T_0} \right)} \dots \dots \dots (1.8)$$

c) The current photo I_{ph} :

The current photo I_{ph} is directly proportional to the solar radiation E (W / m^2) for a chosen temperature T_0 ($^{\circ}$ Kelvin). When the cell is short-circuited, negligible current will flow through the diode. It is given by:

$$I_{ph}|_{T_0} = \frac{I_{sc,0}}{E_0} \cdot E = C_1 \cdot E \dots \dots \dots (1.9)$$

$$I_{ph} = I_{ph}|_{T_0} \cdot (1 + k_0(T - T_0)) \dots \dots \dots (1.10)$$

$$k_0 = \frac{I_{sc}|_{T_2} - I_{sc,0}}{T_2 - T_0} \dots \dots \dots (1.11)$$

With K_0 temperature coefficient of I_{ph} (usually given by the manufacturer on the datasheet as a percentage change per degree Celsius).

I.4.3 External parameters of a photovoltaic cell:

These parameters can be determined from current-voltage curves, or from the characteristic equation. The most common are the following:

a) The short-circuit current I_{sc} :

This is the current for which the voltage at the terminals of the cell or the PV generator is zero. It is directly proportional to the radiant energy received, to the ambient temperature, to the speed of circulation of the ambient air and to the surface of the cell. In the ideal case (R_s null and R_{sh} infinite), this current merges with the current photo I_{ph}

$$I_{sc} = I_{ph} \dots \dots \dots (1.12)$$

Otherwise, by canceling the voltage V in equation (1.2), we obtain:

$$I_{sc} = I_{ph} - I_0 \left(e^{q \left(\frac{R_s I_{sc}}{nKT} \right)} - 1 \right) - \frac{I_{sc} R_s}{R_p} \dots \dots \dots (1.13)$$

b) The open circuit voltage V_{oc} :

For an infinitely large load (open circuit), the output current is zero and the voltage at the terminals of the cell is maximum. This voltage hardly varies with the light intensity is called open circuit voltage V_{oc} (open-circuit).

From equation (1.4), we can write:

$$V_{oc} = \frac{AkT}{q} \ln \left(\frac{I_{ph}}{I_s} + 1 \right) = V_{th} \ln \left(\frac{I_{ph}}{I_s} + 1 \right) \dots \dots \dots (1.14)$$

c) The FF Form factor:

We call form factor FF, the ratio between the maximum value of the power that can be extracted PMPP from the solar cell under the conditions of standardized measurements, and the product V_{oc} , I_{sc} [6]:

$$FF = \frac{V_{MPP} I_{MPP}}{V_{oc} I_{sc}} \dots \dots \dots (1.15)$$

Its represents the measure of then quality of the solar cell. This value for a crystalline solar cell is between 0.7 and 0.8. It decreases as the temperature of the cell increases.

d) The efficiency η :

The Photovoltaic efficiency is a very important factor for photovoltaic components, it is defined as the ratio between the maximum power delivered by the cell, P_{max} and the power of the incident solar radiation P_i .

$$\eta_m = \frac{P_{max}}{P_i} = \frac{I_m V_m}{E_s} \dots \dots \dots (1.16)$$

The performance of solar panels depends on geographic location, cloud cover, time of year, etc.

e) The characteristic power of a P cell:

Under fixed ambient operating conditions; lighting, temperature, ambient air circulation speed, etc., the electric power P (W) available at the terminals of a photovoltaic cell is equal to the product of the direct current supplied I by a direct voltage V.

$$P = V \times I \dots \dots \dots (1.17)$$

Where :

- P (W): Power measured at the terminals of the photovoltaic cell;
- V (V): Voltage measured at the terminals of the photovoltaic cell;
- I (A): Current intensity measured at the terminals of the photovoltaic cell.

f) Maximum power:

The maximum power, P_{max} of a cell corresponds to the point for which the product of the voltage and the current is maximum.

$$P_{MPP} = V_{MPP} \times I_{MPP} \dots \dots \dots (1.18)$$

Mathematically, we get this point as follows:

$$\frac{\partial P}{\partial V} = \frac{\partial (IV)}{\partial V} = I + V \frac{\partial I}{\partial V} = 0 \dots \dots \dots (1.19)$$

I.5 Photovoltaic module:

The PV cells are connected in series to form the photovoltaic module, the photovoltaic module is generally made up of 36 cells in series.

Several modules form a photovoltaic panel, several panels form a photovoltaic field or array.

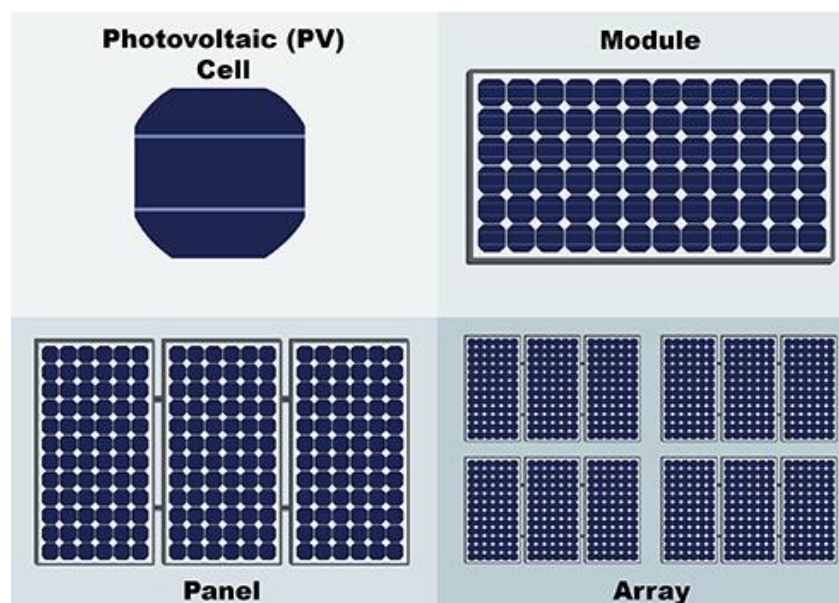


Figure I. 11: a cell, a module , a panel and a photovoltaic array.

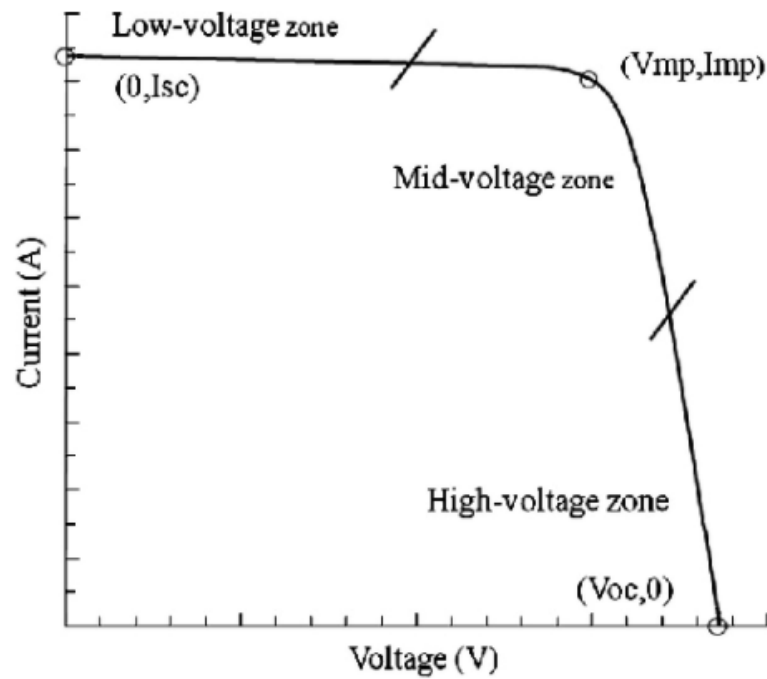


Figure I. 12 : $I=f(v)$ characteristic of a photovoltaic module and operating zones.

The operation of the module is essentially characterized by three zones:

- Low-Voltage Zone : The current I is given almost constant; the module behaves like a current generator (practically constant with a value close to I_{sc}). The operation of the module in this zone is characterized by: low powers, high currents and low voltages.
- High-Voltage Zone : Region corresponding to high values of R_{sc} , the module behaves like an open circuit voltage generator V_{oc} . The operation of the module in this zone is characterized by: low powers, small currents and high voltages.
- Mid-Voltage Zone : The operation of the module in this zone is characterized by high powers, acceptable currents and voltages [7] it corresponding to the curve of the characteristic, it is the intermediate region between the two preceding zones, it represents the region preferred for generator operation where the optimum point (characterized by maximum power) can be determined.

I.5.1 Grouping of photovoltaic cells:

a) In parallel:

A parallel association of (NP) cell figure (I.9b) is possible and makes it possible to increase the output current of the generator thus created. In a group of identical cells

connected in parallel, the cells are subjected to the same voltage and the resulting characteristic of the group is obtained by adding the currents [8].

$$I_{scNP} = N_P \times I_{sc} \dots \dots \dots (1.20)$$

$$V_{oc} = V_{ocNP} \dots \dots \dots (1.21)$$

I_{scNP} : The sum of the cost circuit currents of (NP) cell in parallel.

V_{ocNP} : The open circuit voltage of (NP) cells in parallel.

b) In series:

An association of (N_s) cells in series in FIG. (I.9a) makes it possible to increase the voltage of the photovoltaic generator. The cells are then traversed by the same current and the characteristic resulting from the series grouping is obtained by adding the elementary voltages of each cell. The equation summarizes the electrical characteristics of a series association of (N_s) cells [9].

$$V_{ocNS} = N_s \times V_{oc} \dots \dots \dots (1.22)$$

$$I_{scNS} = I_{sc} \dots \dots \dots (1.23)$$

V_{ocNS} : The sum of the open circuit voltages of N_s cells in series.

I_{scNS} : The short-circuit current of N_s cells in series.

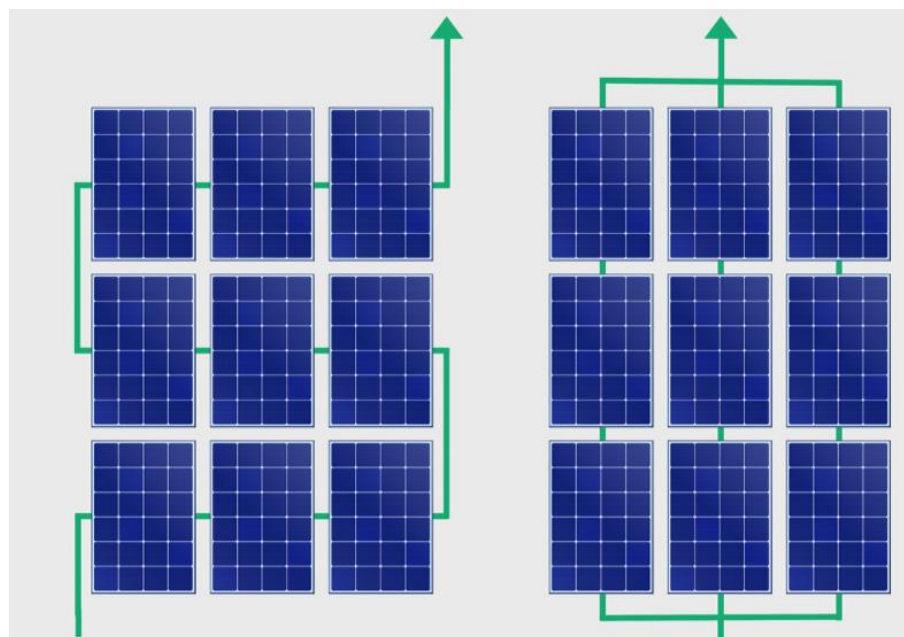


Figure I. 13: Connection of Solar Panels in Serie and parallel.

$$P_{\text{generator}} = N_{ms} \cdot N_{BP} \cdot P_{\text{module}} \dots\dots\dots(1.24)$$

$$V_{\text{generator}} = N_{ms} \cdot V_{\text{module}} \dots\dots\dots(1.25)$$

$$I_{\text{generator}} = N_{BP} \cdot I_{\text{module}} \dots\dots\dots(1.26)$$

$$R_{s \text{ generator}} = R_{s \text{ module}} \cdot \frac{N_{ms}}{N_{BP}} \dots\dots\dots(1.27)$$

N_{ms} : Number of modules associated in series.

N_{BP} : Number of parallel branches.

I.6 Effects of Climatic Variations on the Photovoltaic module:

I.6.1 Influence of illumination:

Figure (1.10a) illustrates the variation of the power delivered by the generator as a function of the voltage for different illumination values, which allows us to deduce the influence of illumination on the characteristic $P(V)$ [10]

Figure (1.10b) shows the influence of illumination on the characteristic $I = f(V)$. At a constant temperature, it is observed that the current undergoes a significant variation, but on the other hand the voltage varies slightly. Because the short-circuit current is a linear function of the illumination while the open circuit voltage is a logarithmic function [11.12]

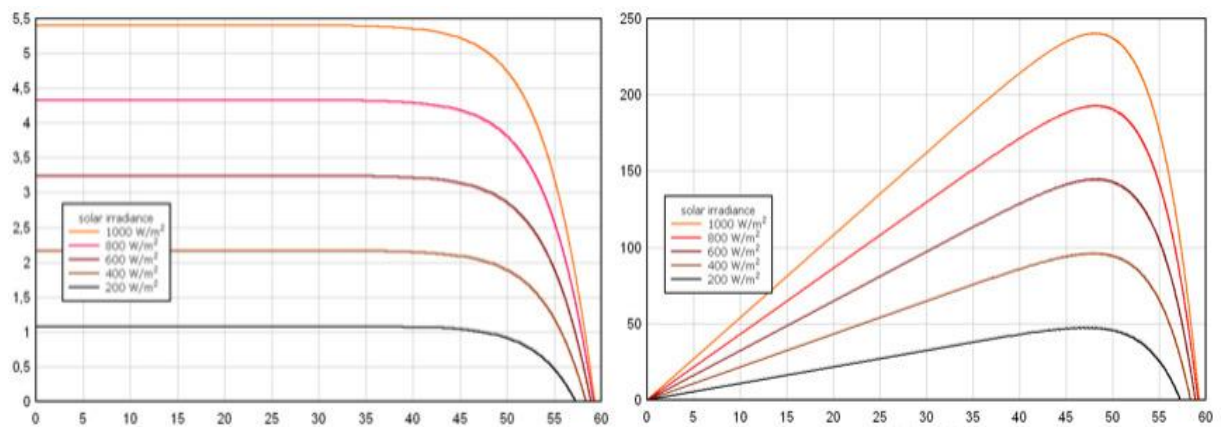


Figure I.14: The influence of illumination on $P = f(V)$, and $I = f(V)$.

I.6.2 Influence of temperature:

Figure (I.11a) illustrates the variation of the power delivered by the generator as a function of the voltage for different values of the temperature, which allows us to deduce the influence of the temperature on the characteristic $P(V)$ [10].

Figure (1.11b) shows the influence of temperature on the characteristic $I = f(V)$. It is essential to understand the effect of changing the temperature of a solar cell on the characteristic $I = f(V)$. The current depends on the temperature since the current increases slightly as the temperature increases, but the temperature negatively affects the voltage of the circuit opens. As the temperature increases the open circuit voltage decreases. Consequently the maximum power of the generator undergoes a decrease [11].

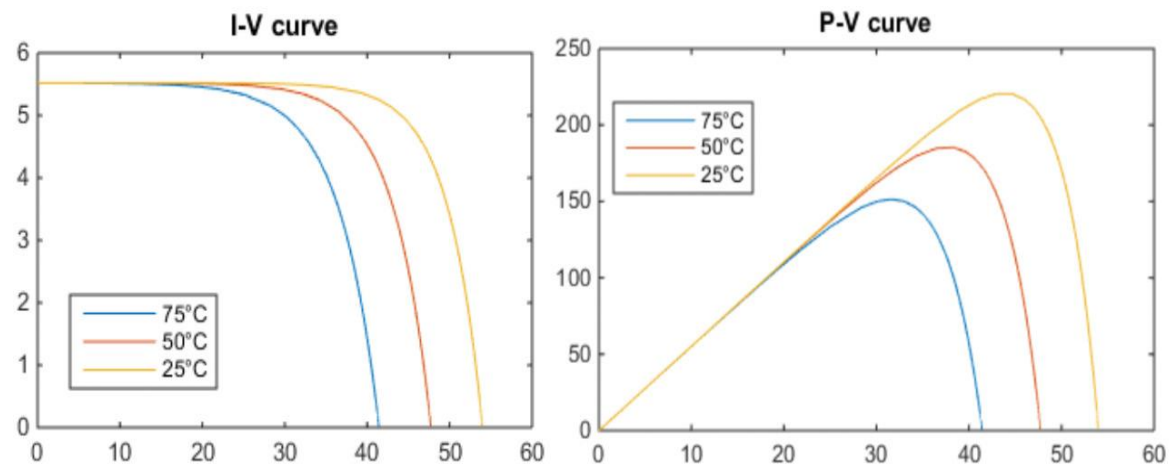


Figure I. 15: The influence of temperature on the characteristics $P = f(V)$, and $I = f(V)$.

I.7 Applications of photovoltaic energy:

Apart from space applications at the origin of the development of photovoltaic techniques and applications in electronics (powering calculators, watches, etc.), there are two main families of applications, namely:

I.7.1 Stand-alone applications:

For supplying sites isolated from the electricity distribution network (housing, radio relay, pumping, beaconing at sea, rural electrification in southern countries, etc.);

I.7.2 Non-autonomous applications:

Its possible to use a photovoltaic generator in a non-autonomous way, by connecting it to the public electricity distribution network. We will then have a small electricity production plant, the energy of which will either be consumed on site by the owner, or sold on the network. In the event of excess production, the photovoltaic generator supplies the network and conversely, the network supplies the distribution in the event of a deficit or outside solar production. The whole is fully automated and managed by one or more inverters.

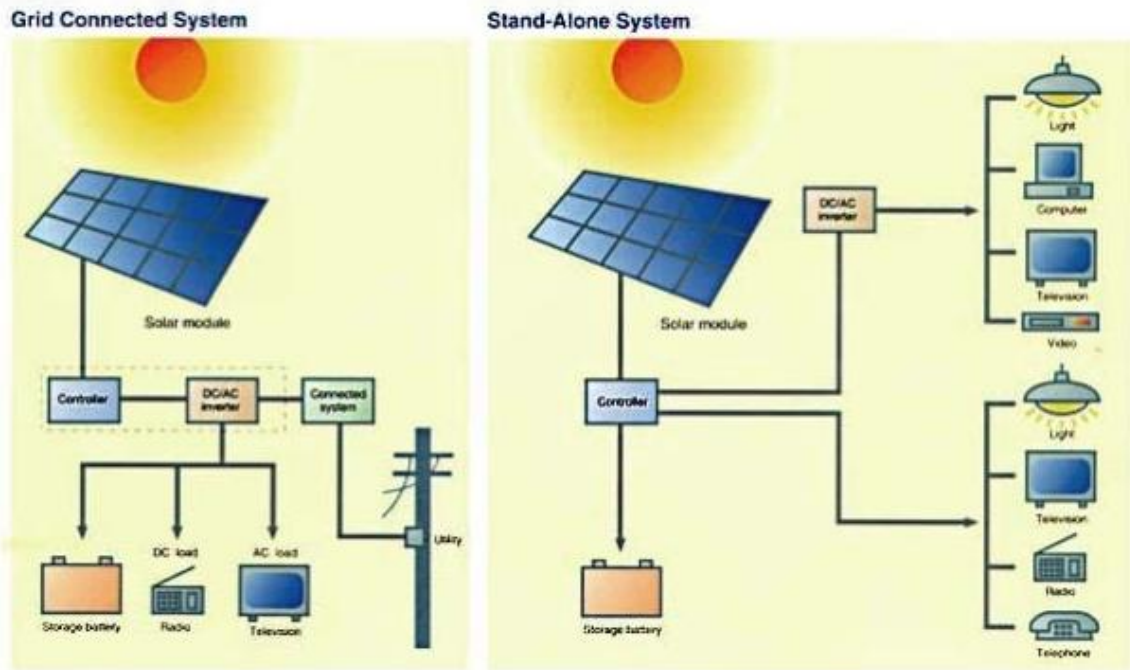


Figure I. 16:Example of an installation isolated or coupled to the network.

I.8 Direct connection (source -load):

The simplest system that can be designed consists of a photovoltaic generator (PVG) and a continuous type load (DC) which directly uses the power supplied by the PVG. This power strongly depends on the illumination, the temperature and the nature of the load. The direct connection between the photovoltaic panel and the load is very widespread due to its simplicity of implementation, as well as its minimal cost due fundamentally to the absence of electronics except for a necessary anti-return diode. sometimes to avoid a possible return of current (figure I.13).

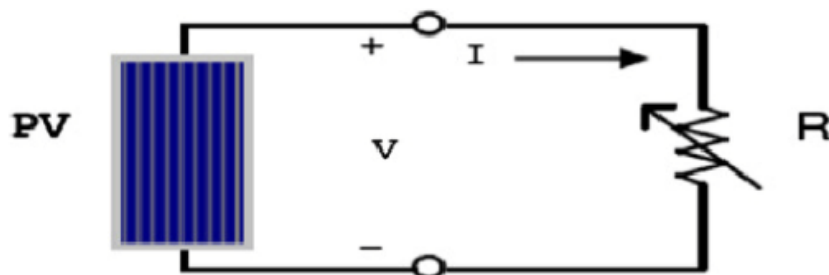


Figure I. 17: PV module is directly connected to a (variable) resistive load.

Unfortunately this configuration does not offer any "setting" parameters. The power supplied by the photovoltaic module is fixed by the intersection between the current-voltage (I-V) characteristic of the PVG and that of the load. The power transfer will therefore not be able to remain optimized when the characteristics fluctuate.

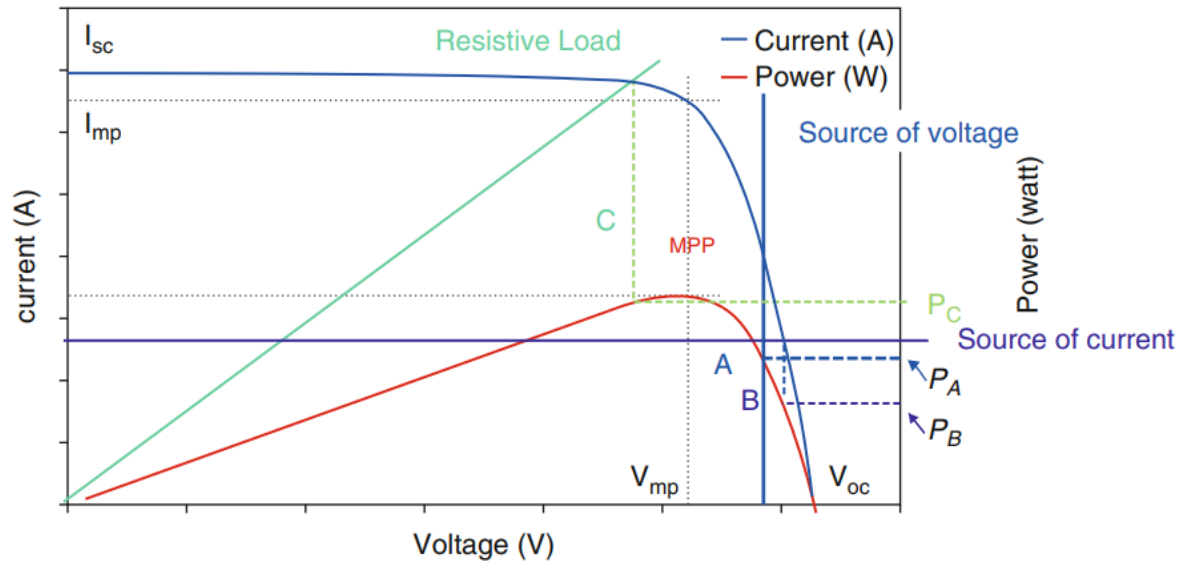


Figure I. 18: PVG operating points in direct connection to the load.

Rather, a PVG can be connected directly to three types of loads:

- A DC voltage source type load,
- A DC current source type load,
- A purely resistive load.

In figure I.14, the characteristics $I(V)$ and $P(V)$ of a PVG are schematized thus the operating point where the power supplied by the generator is maximum (P_{max}) corresponds to the operating point MPP. The points of intersection between the electrical characteristic of the PVG and that of the different loads are respectively

- Point A for a purely resistive load.
- Point B for a DC voltage source type load.
- Point C for a DC current source type load.

As previously illustrated there are three respective operating points A, B, C can be identified providing power, P_A , P_B and P_C . These figures show that the PVG is badly exploited and does not provide maximum power [13].

I.9 Advantages and disadvantages of a PV installation:

I.9.1 Advantages:

- First, high reliability. The installation has no moving parts which make it particularly suitable for remote areas. This is the reason for its use on spacecraft.
- Then, the modular nature of the photovoltaic panels allows a simple and adaptable assembly to various energy needs. The systems can be sized for power applications ranging from milliwatt to megawatt.
- The operating cost is very low given the reduced maintenance and it does not require fuel, transport or highly specialized personnel.
- Photovoltaic technology has ecological qualities because the finished product is non-polluting, silent and does not disturb the environment, except by occupying space for large-scale installations [3].

I.9.1 Disadvantages:

- The manufacture of the photovoltaic module is high technology and requires high cost investments.
- The actual conversion efficiency of a module is low, in the order of 10-15%, with a theoretical limit for a cell of 28%. Photovoltaic generators are only competitive with diesel generators for low energy demands in remote areas.
- The low efficiency of photovoltaic panels can be explained by the very functioning of the cells. To be able to move an electron, the energy of the ion must be at least equal to 1 eV. All incident rays with lower energy will therefore not be transformed into electricity. Likewise, light rays whose energy is greater than 1 eV will lose this energy, the rest will be dissipated in the form of heat.
- Dependent on weather conditions.
- When the storage of electrical energy in chemical form (battery) is required, the cost of the generator is increased.
- The storage of electrical energy still poses many problems.

I.10 conclusion:

This chapter, divided into two parts, allowed us first of all to define the different sources of global energy; namely renewable and non-renewable energies considering that solar energy is the energy of the future.

Secondly, we presented an overview of photovoltaic energy, the operating principle of a photovoltaic cell, the use of its current voltage characteristic to calculate its various physical parameters. We have also seen the effect of climate change on the $I = f(V)$ characteristic of the PVG. In addition, its operating point depends on the load it supplies.

In order to extract the maximum power available at the terminals of the PVG at all times, we introduce an adaptation stage between the generator and the load, hence the aim of the second chapter.

CHAPTER II

MPPT Problematic

Chapter II

MPPT Problematic

II.1 Introduction:

Photovoltaic (PV) systems find increased use in electric power technologies. The main drawbacks of PV systems are high fabrication cost and low energy-conversion efficiency, which is partly caused by their nonlinear and temperature-dependent V–I and P–I characteristics. To overcome these drawbacks, three essential approaches can be followed:

- 1) Improving manufacturing processes of solar arrays: many research efforts have been performed with respect to materials and manufacturing of PV arrays.
- 2) Controlling the insulation input to PV arrays: the input solar energy is maximized using sun-tracking solar collectors or rearranging the solar-cell configurations of PV arrays with respect to changes in environmental conditions [16].
- 3) Using maximum power point tracking (MPPT).

A change in the solar irradiation or the temperature results in a shift of the MPP over a wide range, Instantaneous shading conditions and ageing of PV cells also affect the MPP locus. In addition, the load electrical characteristics may also vary [17].

As previously mentioned, the MPPT is the technique that ensures that the PV panel under any change in irradiance and cell temperature conditions gives the maximum available power. In other words, there is a need to track the MPP to maximize the power drawn off from the PV panel under any circumstance that can possibly cause the system to lose regulation [14].

II.2 Need for maximum power point tracker:

As seen in the PV (power vs voltage) curve of the module in the first chapter, there exists a peak power corresponding to a particular voltage and current. Since the PV module efficiency is low (13%), it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and insulation conditions. Hence maximization of power improves the utilization of the solar PV module. A maximum power point tracker (MPPT) is used for this reason. A dc/dc converter (step up / step down) serves the purpose of transferring maximum power from the solar PV module to the load. A dc/dc converter acts as an interface between the load and the module figure II.1 [18].

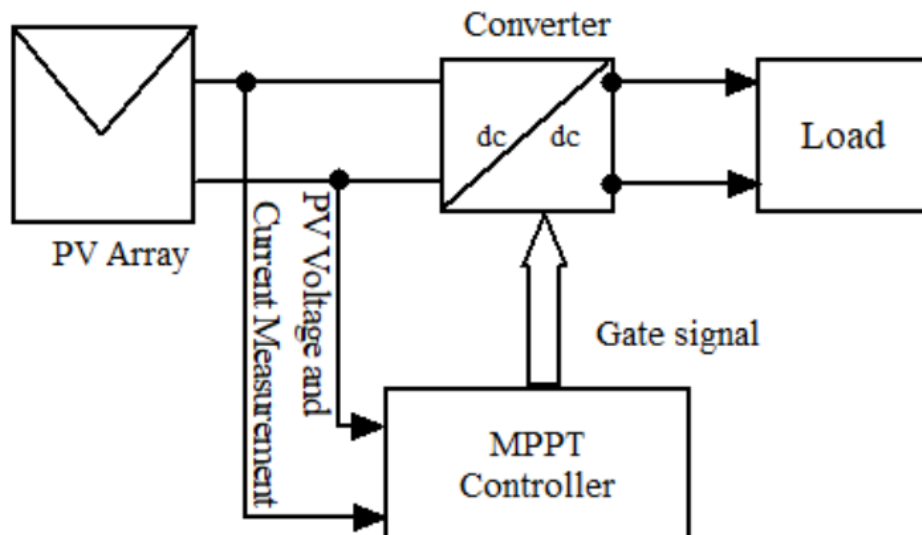


Figure II. 1: Block diagram of a typical MPPT system.

II.3 The maximum power point tracking process:

Figure II.2 illustrates the electrical characteristics of the solar array under a given insulation. The internal impedance of the solar array is low on the right side of the curve and high on the left side. The maximum power point of the solar array is located at the knee of the curve. According to the maximum power transfer theory, the power delivered to the load is maximum when the source internal impedance matches the load impedance. Thus, the impedance seen from the converter side (which can be adjusted by controlling the duty cycle) needs to match the internal impedance of the solar array if the system is required to operate close to the MPP's of the solar array. Most traditional dc/dc converters have an inherent

negative impedance characteristic, as their current increases when the voltage decreases. This behavior is due to the constant input power and the adjustable output voltage of the power supply. If the system operates on the high-impedance (namely, low-voltage) side of the solar array characteristic curve, the solar array terminal voltage will collapse. Therefore; the solar array is required to operate on the right side of the curve to perform the tracking process. Otherwise, the converter will operate with the maximum duty cycle, and the solar array voltage will only change with the insulation. Thus, the system cannot achieve maximum power tracking and might even mistake the present operating point for the MPP [15].

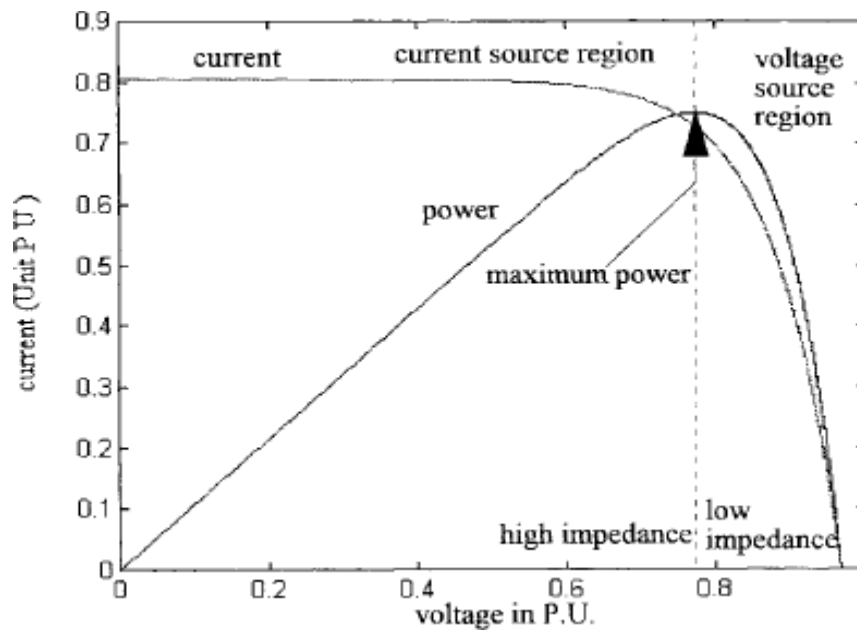


Figure II. 2: Solar array characteristic curves.

II.4 Load matching mechanism to achieve the maximum power point:

As we mentioned in chapter I, when a PV module is directly coupled to a load, the PV module's operating point will be at the intersection of its I-V curve and the load line which is the I-V relationship of the load, in general this operating point is seldom at the PV module's MPP, thus it is not producing the maximum power. A study shows that a direct-coupled system utilizes approximately 31% of the PV capacity[14].

To increase the efficiency of the PV system, a DC-to-DC converter is used as an interface between the PV module and the load to perform the MPPT process and the load matching ($R_{load} = R_{op}$) where R_{load} is the impedance load ; R_{op} is the optimal load for PV.

II.5 DC-DC Converter:

The DC-DC converter is used to supply a regulated DC output with the given DC input. These are widely used as an interface between the photovoltaic panel and the load in photovoltaic generating systems. The load must be adjusted to match the current and voltage of the solar panel so as to deliver the maximum power. DC/DC converters are described as power electronic switching circuits since they convert one form of voltage to another. These may be applicable for conversion of different voltage levels.

Generally three basic types of converters are accountable as per their use. They either step up by boosting voltage at output known as Boost Converter or by stepping down by reducing the voltage known as Buck converters. There is another class of converters used for both stepping up or down the voltage output described as Buck-Boost converters. Buck-Boost converters reverse polarity of output voltage, as such they are sometimes known as inverters.

II.6 Boost Converter:

Boost converter steps up the input voltage magnitude to a required output voltage magnitude without the use of a transformer. The main components of a boost converter are an inductor, a diode, a capacitor and a high frequency switch. These in a coordinated manner supply power to the load at a voltage greater than the input voltage magnitude. The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change. Figure II.3 represents the circuit diagram of DC-DC boost converter.

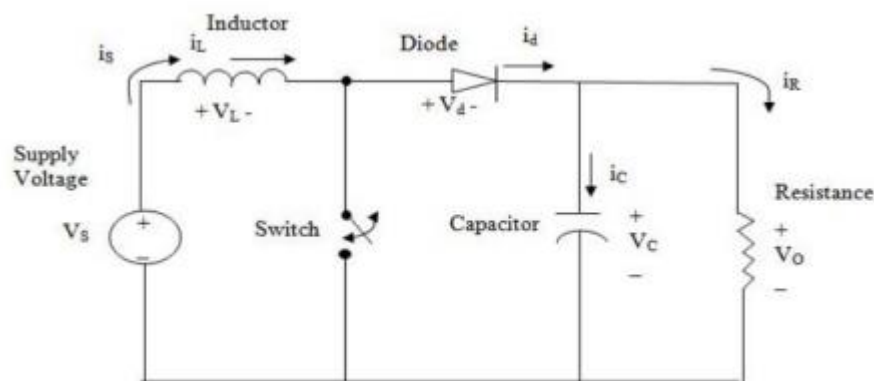


Figure II. 3: Circuit diagram of boost converter.

II.6.1 Modes of Operation:

There are two modes of operation of a boost converter. Those are based on the closing and opening of the switch. The first mode is when the switch is closed; this is known as the charging mode of operation. The second mode is when the switch is open; this is known as the discharging mode of operation

Mode I : Switch is ON, Diode is OFF

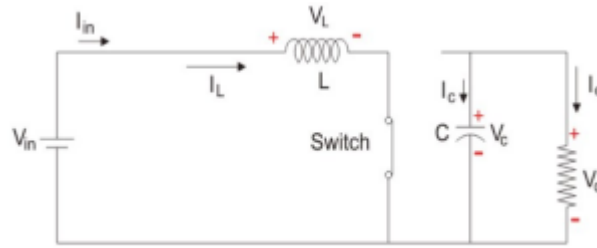


Figure II. 4: Switch ON, Diode OFF .

The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and back to the DC input source. Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF} . We define the time period, T , as $T = T_{ON} + T_{OFF}$ and the switching frequency:

$$f_{\text{switching}} = \frac{1}{T} \quad (2.1)$$

Let us now define another term, the duty cycle:

$$D = \frac{T_{ON}}{T} \quad (2.2)$$

Let us analyze the Boost converter in steady state operation for this mode using KVL:

$$V_{in} = V_L \quad (2.3)$$

$$V_{in} = L \frac{di_L}{dt} \quad (2.4)$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{in}}{L} \quad (2.5)$$

Since the switch is closed for a time $T_{ON} = DT$ we can say that $\Delta t = DT$

$$(\Delta i_L)_{\text{closed}} = \left(\frac{V_{in}}{L} \right) DT \quad (2.5)$$

Mode II: Switch is OFF, Diode is ON:

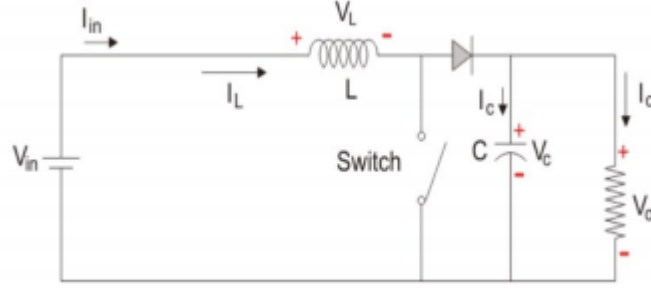


Figure II. 5: Switch OFF, Diode ON.

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

Let us now analyze the boost converter in steady state operation for Mode II using KVL:

$$V_{in} = V_L + V_o \dots \dots \dots (2.6)$$

$$V_{in} = L \frac{di_L}{dt} = V_{in} - V_o \dots \dots \dots (2.7)$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_{in} - V_o}{L} \dots \dots \dots (2.8)$$

Since the switch is open for a *time* $T_{off} = T - T_{on} = T - DT = (1 - D)T$ we can say that $\Delta t = (1 - D)T$

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

$$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0 \dots \dots \dots (2.9)$$

$$\left(\frac{V_{in} - V_o}{L} \right) (1 - D)T + \left(\frac{-V_o}{L} \right) DT = 0 \dots \dots \dots (2.10)$$

$$\left(\frac{V_o}{V_{in}} \right) = \frac{1}{1-D} \dots \dots \dots (2.5)$$

Where V_0 is the output voltage, D is the duty cycle and V_{in} is the input voltage which in this case will be the solar panel voltage.

II.6.2 Waveforms:

Figure II.6 shows the different characteristics of boost converters. It shows the source voltage, source current, inductor current and capacitor current with respect to time for a complete duty cycle

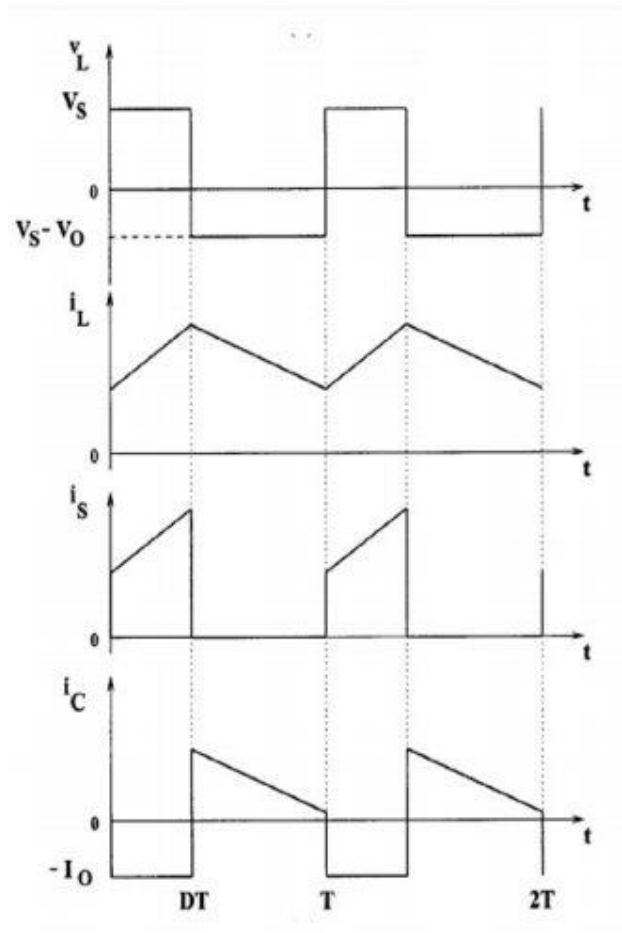


Figure II. 6: Waveforms of boost converter .

It is assumed that the switch is made ON and OFF at a fixed frequency and let the period corresponding to the switching frequency is T . Given that the duty cycle is D , the switch is ON for a period equal to DT and the switch is OFF for a time interval equal to $(1-D) T$. The inductor is continuous and is greater than zero.

II.6.3 .Modeling of Boost Converter:

The DC-DC boost converter circuit consists of Inductor (L), Diode (D), Capacitor (C), load resistor (RL), the control switch (S). The components are connected in such a way with the input voltage source (Vin) so as to step up the voltage. The duty cycle of the control switch controls the output voltage of the boost converter. Hence by varying the ON time of the switch, the output voltage can be varied. Thus, for the duty cycle “D” the average output voltage can be calculated using:

$$\left(\frac{V_o}{V_{in}}\right) = \frac{1}{1-D} \dots\dots\dots(2.6)$$

Where, V_{in} and V_o are the input and output voltage of the converter respectively and D is the duty cycle of the control switch. In an ideal circuit, the output power of the converter is equal to input power which yields

A. Selection of Inductor:

The inductor value of the boost converter are calculated using:

$$L = \frac{V_{in}}{f_s \Delta I_L} \dots\dots\dots(2.7)$$

Where, f_0 is the switching frequency and ΔI_L is the input current ripple. Current ripple factor (CRF) is the ratio between input current ripple and output current. For good estimation of inductor value CRF should bound within 30%.

The current rating of inductor should be always higher than that of the maximum output current.

$$\Delta I_L / I_o = 0.3 \dots\dots\dots(2.8)$$

B. Selection of Capacitor:

The capacitor value can be obtained from:

$$C = I_o / (f_s \Delta V_o)^D \dots\dots\dots(2.9)$$

Where ΔV_o is the output voltage ripple which is usually considered as 5% of the output voltage which yields

$$\Delta V_o / V_o = 5\% \dots\dots\dots(2.10)$$

Conclusion:

As we have seen in this chapter, MPPT is an important process for the PV system to deliver maximum power to the load and also to increase the efficiency. A DC-DC converter is included in the system between the load and the source to achieve maximum power transfer between the source and the load. Boost converter is used when the load impedance is less than the source impedance .

By changing the duty cycle of the converter for each weather condition (temperature and radiation), the impedance matching can be reached using MPPT algorithms and that will be the aim of the next chapter.

CHAPTER III

MPPT methods

Chapter III

MPPT Methods

III.1 Introduction:

As was previously explained, MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array.

Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others. A complete review of 19 different MPPT algorithms can be found in [21].

Among these techniques, the P&O and the InCond algorithms are the most common. These techniques have the advantage of an easy implementation but they also have drawbacks, as will be shown later. Other techniques based on different principles are fuzzy logic control, neural network, fractional open circuit voltage or short circuit current, current sweep, etc. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the V-P curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented as in [14]. In the next section the most popular MPPT techniques are discussed.

III.2 Hill-climbing techniques:

Both P&O and InCond algorithms are based on the “hill-climbing” principle, which consists of moving the operation point of the PV array in the direction in which power increases [14] and [23]. Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant [23]. The advantages of both methods are the simplicity and low computational power they need. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions [20], [23]-[28]. These drawbacks will be explained later.

III.2.1 Perturb and observe :

The P&O algorithm is also called “hill-climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter [21]. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. As can be seen in Figure 11, on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

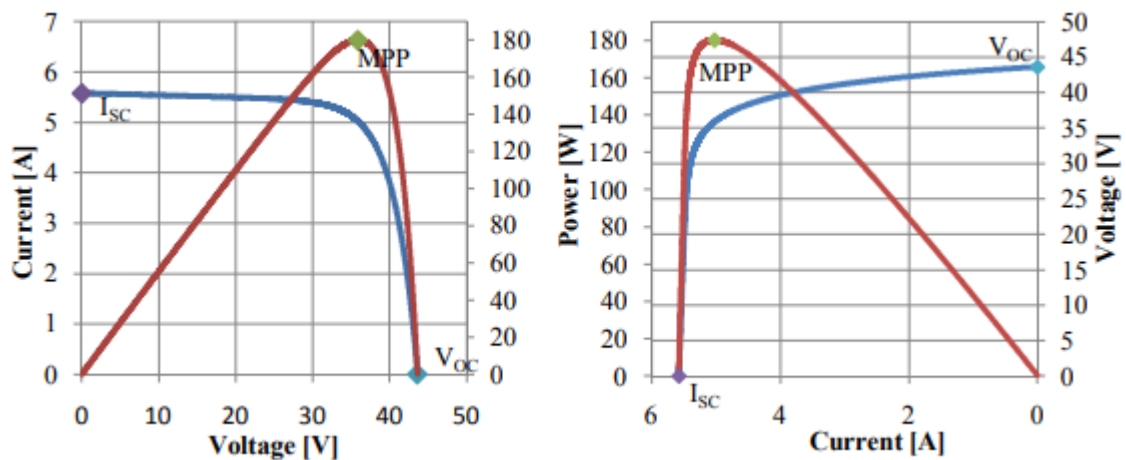


Figure III. 1: PV panel characteristic curves.

If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented [21]. The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP. This problem is common also to the InCond method, as was mentioned earlier. A scheme of the algorithm is shown in Figure III.2.

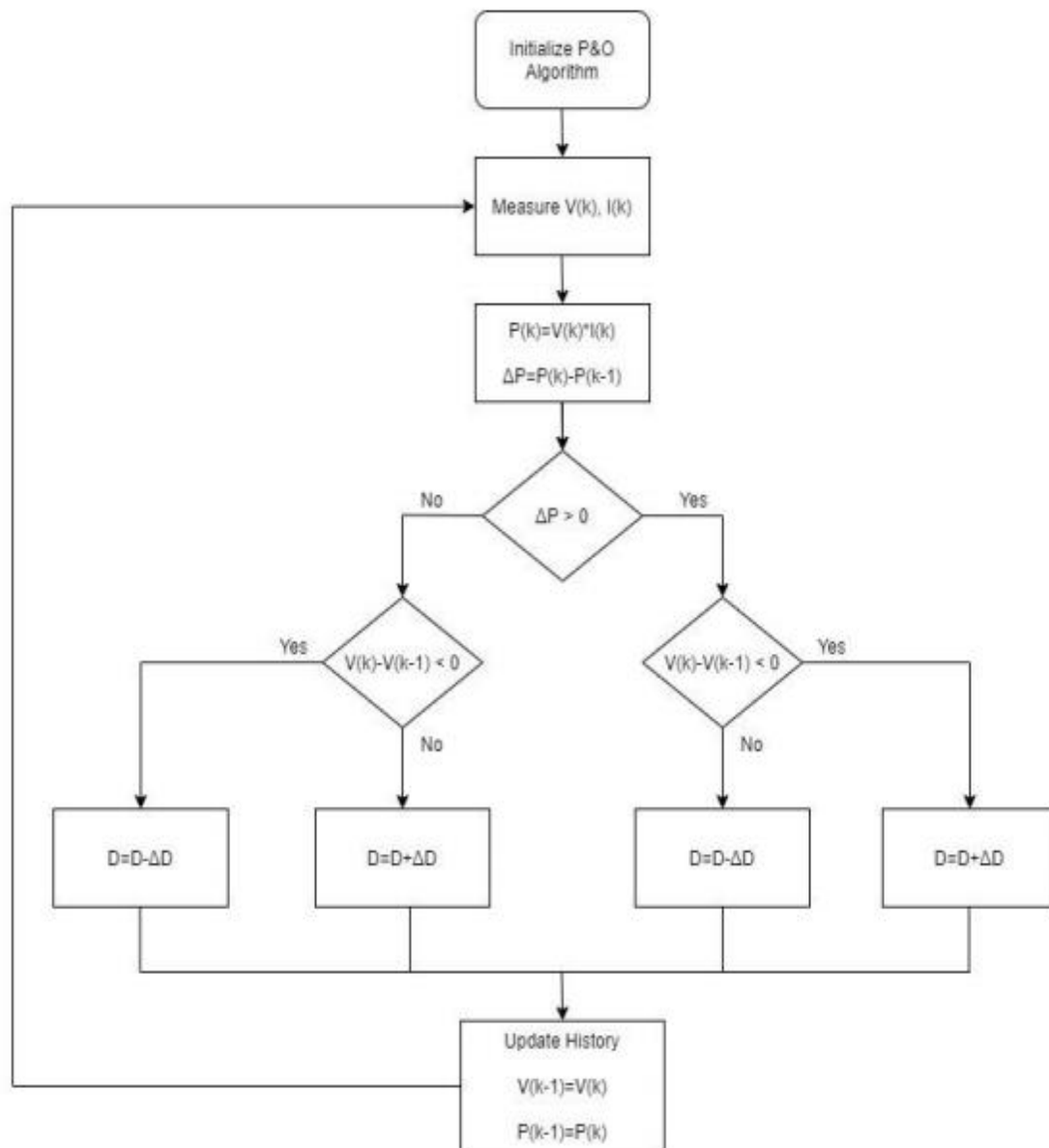


Figure III. 2: Flowchart of perturb and observe algorithm.

III.2.2 Incremental conductance (IC) method :

The incremental conductance method uses the slope of the output power, and the voltage of the solar array is equal to zero at the maximum power point. The slope is positive on the left of MPP, negative on the right side of MPP, and it can be seen in figure III.3:

- $\frac{dP}{dV} = 0, \text{ at MPP} \dots\dots\dots(3.1)$

- $\frac{dP}{dV} > 0, \text{ left of MPP} \dots\dots\dots(3.2)$

- $\frac{dP}{dV} < 0, \text{ right of MPP} \dots\dots\dots(3.3)$

According to the above explanation, it can be written followed,

- $\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V \frac{dI}{dV} \cong I + V \frac{\Delta I}{\Delta V} \dots\dots\dots(3.4)$

(3.1), (3.2), (3.3) can be rewritten as:

- $\frac{dI}{dV} = -\frac{I}{V}, \text{ at MPP} \dots\dots\dots(3.5)$

- $\frac{dI}{dV} > -\frac{I}{V}, \text{ left of MPP} \dots\dots\dots(3.6)$

- $\frac{dI}{dV} < -\frac{I}{V}, \text{ right of MPP} \dots\dots\dots(3.7)$

The flowchart of the IC method can be seen in figure III.3

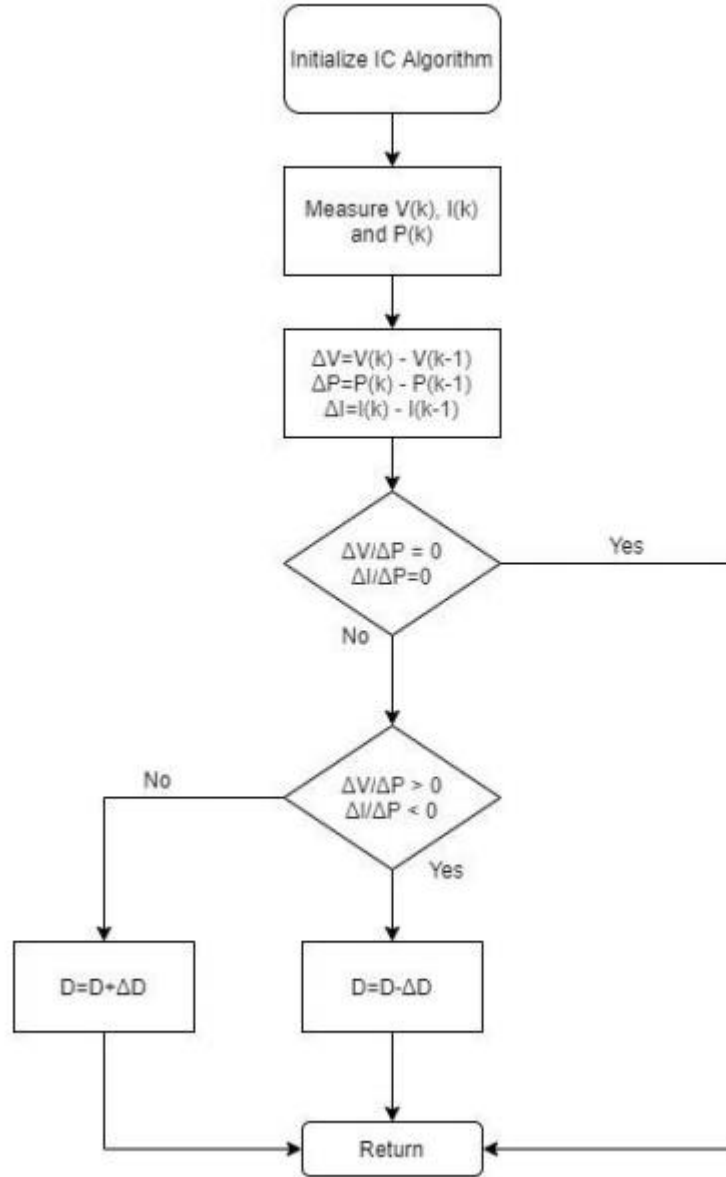


Figure III. 3: Flowchart of incremental conductance algorithm.

In both P&O and InCond schemes, how fast the MPP is reached depends on the size of the increment of ΔD .

The drawbacks of these techniques are mainly two. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly [20], [23]-[26]. In case of step changes they track the MPP very well, because the change is instantaneous and the curve does not keep on changing. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, as can be seen in Figure III.4, so the changes in the voltage and current are not only due to the perturbation of the voltage. As a consequence it is not possible for the algorithms to

determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation.

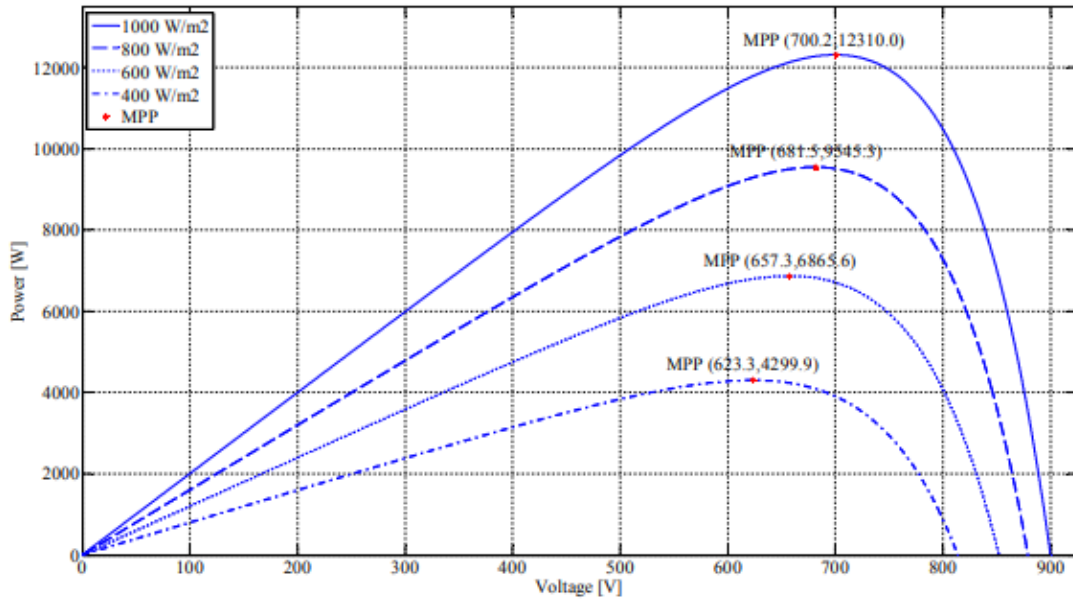


Figure III. 4: P-V curve depending on the irradiation.

The other handicap of both methods is the oscillations of the voltage and current around the MPP in the steady state [20], [25], [27] and [28]. This is due to the fact that the control is discrete and the voltage and current are not constantly at the MPP but oscillating around it. The size of the oscillations depends on the size of the rate of change of the reference voltage. The greater it is, the higher is the amplitude of the oscillations. However, how fast the MPP is reached also depends on this rate of change and this dependence is inversely proportional to the size of the voltage increments. The traditional solution is a trade off: if the increment is small so that the oscillations decrease, then the MPP is reached slowly and vice versa, so a compromise solution has to be found.

To overcome these drawbacks some solutions have been published in recent years. Regarding the rapid change of the irradiation conditions, Sera et al. published in [23] and [24] an improved P&O method, called “dP-P&O”, in which an additional measurement is performed without perturbation in the voltage and current. In this way, every three consecutive samples the effect of the perturbation in the voltage (current) and the effect of the change in the atmospheric conditions can be evaluated so that the increment in the power used in the algorithm only contains the effect caused purely by the MPPT algorithm. Then the correct decision about the direction of the next perturbation can be taken. The efficiency

of the tracking is improved. Although the method was tested using irradiation slopes, they were not the ones proposed in the new European Standard EN 50530 [22].

A different solution is suggested in [28], which considers the traditional P&O algorithm, in which the perturbation amplitude is tuned constantly taking into account the previous changes in the power. It also includes a stage in which the latest increment in the power is compared with the latest perturbation amplitude to determine if the power increment was due to a change in the irradiation. If this is the case, then the voltage perturbation is set to the same direction as the change in the power condition. The steady state error and the tracking speed are improved, but the algorithm has only been tested with irradiation step changes and not with the irradiation slopes proposed in [22].

In relationship with the oscillations around the MPP in steady state, Zhang et al. proposed in [27] a variable perturbation step for the P&O algorithm to reduce the oscillation around it. This modified P&O method determines also if the operating point is near to or far from the MPP and adjusts the size of the perturbation according to that: if the operating point is near to the MPP, the perturbation size is reduced and if the point is far, then it is increased. This technique improves the convergence speed and reduces the oscillation around the MPP. A similar technique is found in [27]: a variation of the traditional P&O algorithm in which the amplitude of the voltage perturbation is adapted to the actual operating conditions: large perturbation amplitudes are chosen far from the maximum whereas small ones are used near the MPP. The proposed algorithm requires initial panel identification and has to be tuned for each plant. With this technique the dynamic response and the steady state stability are improved. Unfortunately, the last two algorithms do not improve the tracking under changing irradiance conditions. Although the authors claim the performance is better, the algorithms have only been tested with irradiation step changes but not with irradiation ramps as proposed in the European Standard mentioned above [22].

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Many papers have been published about optimizing the parameters of these algorithms for different hardware configurations. In [20] the sample frequency for P&O is optimized and in [25] it is shown how the P&O MPPT parameters must be customized to the dynamic behaviour of the specific converter adopted. It has been traditionally said that the performance of InCond algorithm is better than the P&O. However, according to [20] and [25] the performance is similar if the parameters of the P&O method are optimized. In any case, both algorithms are based on the same principle and have the same problem so they have been analyzed together.

III.2.3 Other “hill climbing” MPPT methods :

There are other three techniques revised in [21] that can be grouped with the hill climbing algorithms: ripple correlation control (RCC), dP/dV or dP/dI Feedback control and slide control.

RCC uses the ripple imposed by the power converter on the PV array to track the MPP. It correlates dp/dt with di/dt or dv/dt , to drive the power gradient to zero, which happens when the MPP is reached. According to [29] $\frac{dp}{dt} \cdot \frac{di}{dt}$ or $\frac{dp}{dt} \cdot \frac{dv}{dt}$ are positive to the left of the MPP, negative to the right and zero at the MPP. Actually the same criteria is used by the InCond algorithm but expressed in a different form, thus it will suffer the same problems. In

fact, it has been only tested with irradiation steps, which are not appropriate to test the dynamic performance. Besides, it needs low switching frequencies to have enough ripple so the correct decisions can be made and it is an analog technique. On the contrary, inverters are nowadays controlled digitally with DSPs, so this method does not show any advantage to the P&O or InCond.

dP/dV or dP/dI Feedback control is a technique which computes the slope of the P-V or P-I characteristic curve and feeds it back to the controller in order to drive it to zero, as they are zero at the MPP. Again this is another implementation of the InCond algorithm, so it has the same advantages and disadvantages.

Finally, in the slide control, the switching function used is again dP/dV , thus the same problems as with the InCond algorithm can be expected under changing irradiation.

To summarise, the last three MPPT methods are based on the same principles as the P&O and the InCond algorithms, so they have the same advantages and disadvantages. All hill-climbing MPPT methods depend on the PV array's V-P or I-P characteristics, which vary with temperature and irradiation, therefore these MPPT methods can be confused when the irradiation or temperature are changing, as it is explained in [23]. Finally, the other hill-climbing MPPT methods do not offer any improvement to the original P&O and InCond algorithms.

III.3 Fuzzy logic control:

The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. Microcontrollers have also helped in the popularization of fuzzy logic control [21].

The fuzzy logic consists of three stages: fuzzification, inference system and defuzzification. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions, like the ones in Figure 15, are used to associate a grade to each linguistic term. The number of membership functions used depends on the accuracy of the controller, but it usually varies between 5 and 7 [21], [30]-[31]. In Figure 15 seven fuzzy levels are used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The values a , b and c are based on the range values

of the numerical variable. In some cases the membership functions are chosen less symmetric or even optimized for the application for better accuracy [21], [31].

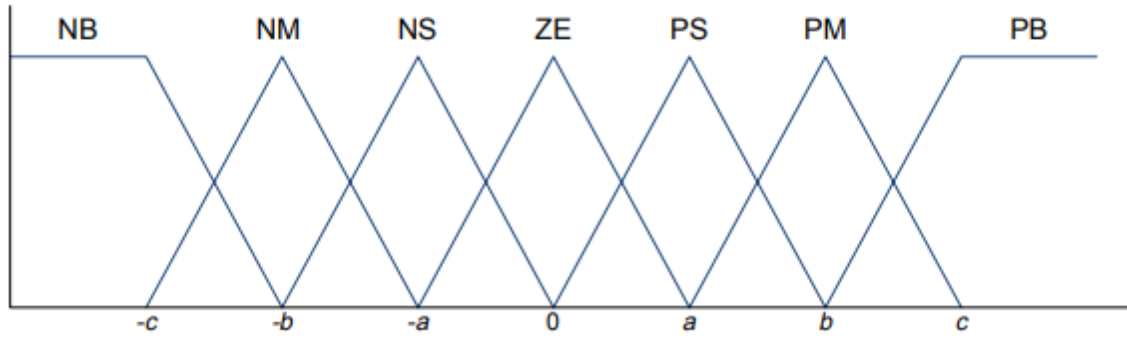


Figure III. 5: Membership functions.

The inputs of the fuzzy controller are usually an error, E , and the change in the error, ΔE . The error can be chosen by the designer, but usually it is chosen as $\Delta P / \Delta V$ because it is zero at the MPP. Then E and ΔE are defined as follows:

$$E = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \dots \dots \dots (3.8)$$

$$\Delta E = E(k) - E(k-1) \dots \dots \dots (3.9)$$

In other cases $\Delta P / \Delta I$ is used as error [30] or other inputs are considered, as in [25], where ΔU and ΔP are used.

The output of the fuzzy logic converter is usually a change in the duty ratio of the power converter, ΔD , or a change in the reference voltage of the DC-link, ΔV . The rule base, also known as rule base lookup table or fuzzy rule algorithm, associates the fuzzy output to the fuzzy inputs based on the power converter used and on the knowledge of the user. Table I shows the rules for a three phase inverter, where the inputs are E and ΔE , as defined in (7) and (8), and the output is a change in the DC-link voltage, ΔV . For example, if the operating point is far to the right of the MPP, E is NB, and ΔE is zero, then to reach the MPP the reference voltage should decrease, so ΔE should be NB (Negative) to move the operating point towards the MPP.

E\dE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table III. 1: Rules Base table.

The last stage of the fuzzy logic control is the defuzzification. In this stage the output is converted from a linguistic variable to a numerical crisp one again using membership functions as those in Figure III. 6. There are different methods to transform the linguistic variables into crisp values. It can be said that the most popular is the center of gravity method. However the analysis of these methods is beyond the scope of this thesis.

The advantages of these controllers, besides dealing with imprecise inputs, not needing an accurate mathematical model and handling nonlinearity, are fast convergence and minimal oscillations around the MPP. Furthermore, they have been shown to perform well under step changes in the irradiation. However, no evidence was found that they perform well under irradiation ramps. Therefore, their performance under the conditions specified in [22] for testing the dynamic MPPT efficiency is unknown. Another disadvantage is that their effectiveness depends a lot on the skills of the designer; not only on choosing the right error computation, but also in coming up with an appropriate rule base [21].

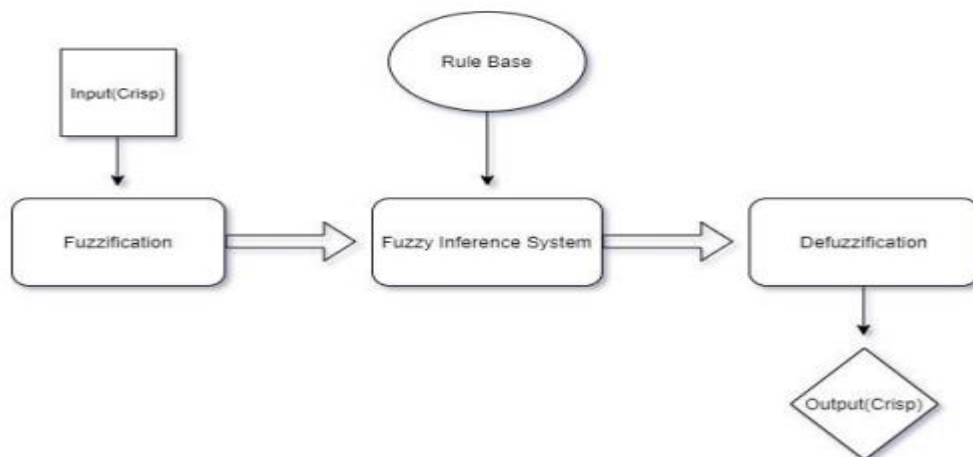


Figure III. 7: Flowchart of the fuzzy logic control.

III.4 Neural networks:

Another MPPT method well adapted to microcontrollers is Neural Networks [21]. They came along with Fuzzy Logic and both are part of the so called “Soft Computing”. The simplest example of a Neural Network (NN) has three layers called the input layer, hidden layer and output layer, as shown in Figure III. 8. More complicated NN’s are built adding more hidden layers. The number of layers and the number of nodes in each layer as well as the function used in each layer vary and depend on the user knowledge. The input variables can be parameters of the PV array such as VOC and ISC, atmospheric data as irradiation and temperature or a combination of these. The output is usually one or more reference signals like the duty cycle or the DC-link reference voltage.

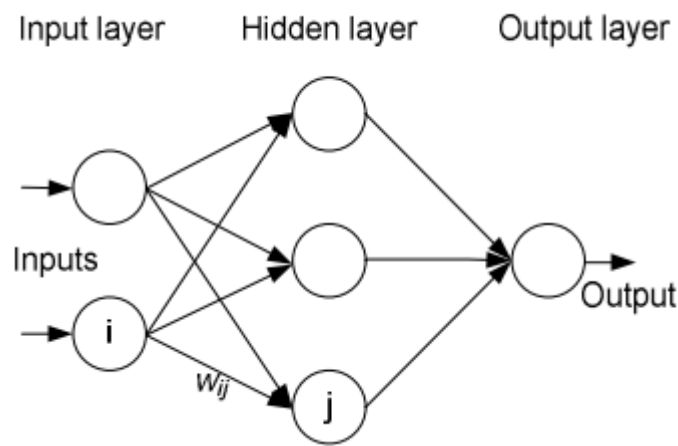


Figure III. 9: Neural network.

The performance of the NN depends on the functions used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted. In Figure 16 the weight between the nodes i and j is labelled as w_{ij} . The weights are adjusted in the training process. To execute this training process, data of the patterns between inputs and outputs of the neural network are recorded over a lengthy period of time, so that the MPP can be tracked accurately.

The main disadvantage of this MPPT technique is the fact that the data needed for the training process has to be specifically acquired for every PV array and location, as the characteristics of the PV array vary depending on the model and the atmospheric conditions depend on the location. These characteristics also change with time, so the neural network has to be periodically trained.

III.5 Fractional open circuit voltage :

This method uses the approximately linear relationship between the MPP voltage (VMPP) and the open circuit voltage (VOC), which varies with the irradiance and temperature [21]:

$$V_{MPP} \approx k_1 V_{OC} \dots \dots \dots (3.10)$$

where k_1 is a constant depending on the characteristics of the PV array and it has to be determined beforehand by determining the VMPP and VOC for different levels of irradiation and different temperatures. According to [21] the constant k_1 has been reported to be between 0.71 and 0.78.

Once the constant of proportionality, k_1 , is known, the MPP voltage VMPP can be determined periodically by measuring VOC. To measure VOC the power converter has to be shut down momentarily so in each measurement a loss of power occurs. Another problem of this method is that it is incapable of tracking the MPP under irradiation slopes, because the determination of VMPP is not continuous. One more disadvantage is that the MPP reached is not the real one because the relationship is only an approximation.

To overcome these drawbacks, some solutions have been proposed, as is reported in [21]. For example, pilot cells can be used to obtain VOC. They are solar cells that represent the PV array's cells and which are not used to produce electricity but to obtain characteristics parameters such as VOC without interfering with the power converters. These pilot cells have to be carefully chosen and placed to represent the PV array characteristics and the irradiation conditions. One drawback of using these pilot cells is that the cost of the system is increased.

Depending on the application, this technique can be used because it is very easy to implement and it is cheap - it does not require DSP or microcontroller control and just one voltage sensor is used [21]. However, according to [21] this method is not valid under partial shading of the PV array because then the constant k_1 changes. To update then k_1 a voltage sweep is proposed though this increases the complexity of the system, the cost increases and there are more power losses during the sweep.

III.6 Fractional short circuit current:

Just like in the fractional open circuit voltage method, there is a relationship, under varying atmospheric conditions, between the short circuit current I_{SC} and the MPP current, I_{MPP} , as is shown by:

$$I_{MPP} \approx k_2 I_{SC} \dots \dots \dots (3.10)$$

The coefficient of proportionality k_2 has to be determined according to each PV array, as in the previous method happened with k_1 . According to [21] the constant k_2 has been reported to be between 0.78 and 0.92.

Measuring the short circuit current while the system is operating is a problem. It usually requires adding an additional switch to the power converter to periodically short the PV array and measure I_{SC} . In [32] I_{SC} is measured by shorting the PV array with an additional field-effect transistor added between the PV array and the DC link capacitor. One other option is shown in [33]: a boost converter is used and the switch of the converter is used to short the PV array. Short circuiting the PV array also leads to a loss of power. One last handicap is that the real MPP is not reached because the proportional relationship is an approximation. Furthermore, k_2 changes if the PV array is partially shaded, which happens due to shades or surface contamination. To overcome this problem, [32] proposes an online tuning of k_2 and [28] a periodical sweep of the PV voltage from open circuit to short circuit to update k_2 and guarantee that the real MPP is reached in the presence of multiple maxima which obviously increases the complexity of the system. Most of the literature using this MPPT technique uses a DSP as controller [21].

III.7 Current sweep:

In this method the I-V characteristic curve is obtained using a sweep waveform for the PV array current. The sweep is repeated at fixed time intervals so the I-V curve is updated periodically and the MPP voltage (V_{MPP}) can be determined from it at these same intervals. How the I-V curve is determined and the function chosen for the sweep waveform can be found in [34].

With this method the real MPP is obtained. On the other hand, the sweep takes certain time during which the operating point is not the MPP, which implies some loss of available power. Strictly speaking, it is not possible to track the MPP under irradiation slopes, because the MPP varies continuously. Only if the sweep is instantaneous the global MPP could be

found, but that is impossible. Furthermore, the implementation complexity is high, the convergence speed is slow and both voltage and current measurements are required. As pointed out in [34] a MPPT method is worth using only if its power consumption is lower than the increase in power it brings to the entire PV system.

Due to the drawbacks and complexity exposed above, this MPPT method is not the best option to track the MPP continuously. However, it can be used as a complement to other methods, for example when initializing the PV system in the morning, to begin the tracking in the real MPP and then change to another algorithm, or to check sometimes during the day if the system is operating at the real MPP. One more application can be checking if there are multiple maxima due to shading conditions.

III.8 Maximum power point current and voltage computation :

IMPP & VMPP computation is a technique in which the MPP is calculated based on the measurements of the irradiance and the temperature using a model of the PV module [21]. The drawbacks are the extra measurements needed, which are sometimes difficult to obtain, and the necessity of an accurate model of the PV array. On the other hand, the MPP is correctly tracked even under changing atmospheric conditions. It can be used in large plants, where the economic investment is huge and a perfect tracking is needed to obtain the maximum available power from the solar arrays.

III.9 PID CONTROLLER

PID (Proportional-Integral-Derivative) controller is one of the earliest conventional industrial controllers. It has many advantages like economic, simple and easy to tune. The Simulink model for the nonlinear system using a conventional PID controller is developed. The mathematical expression for the same is given in equation expressed by equation

$$U(t) = K_p e(t) + K_I \int e(t) dt + K_D \frac{de(t)}{dt}$$

Where, $U(t)$: Control Signal
 $e(t)$: Tracking Error, the difference between the desired and the actual output.
 K_p : Proportional Gain (Tuning Parameter)
 K_I : Integral Gain (Tuning Parameter)
 K_D : Derivative Gain (Tuning Parameter)

III.10 Multiple maxima search :

It has not been considered in this thesis, but when the PV array is shaded the P-V curve presents multiple maxima and most MPPT algorithms including P&O, InCond and fuzzy logic control, cannot determine the global maximum. Usually a local MPP is found, depending on the starting point of the algorithm [14].

In recent years, some algorithms have been proposed to overcome this limitation. The most relevant are reviewed in the introduction of [14], which claims that the most effective is the DIRECT search technique that is based on the dividing rectangles algorithm. If this method is continuously used to track the MPP, the maximum reported efficiency is 97% [14].

However, it can be used periodically to determine where the global maximum is and then change to a traditional algorithm whose efficiency can be over 99% [27]. This could be effective as the shades move slowly during the day. In this way, the losses that occur due to convergence to a local instead of the global MPP, which is a handicap of most traditional algorithms, could be avoided.

III.11 Maximum power point tracking summary :

Most of the MPPT algorithms developed over the past years have been reviewed in the previous sections. Some of them are very similar and use the same principle but expressed in different ways, like the last three algorithms listed in the hill-climbing techniques.

The most popular MPPT algorithms according to the number of publications are P&O, InCond and Fuzzy Logic. It makes sense because they are the simplest algorithms capable of finding the real MPP. However, they have some disadvantages, as discussed earlier. In the following chapter, the performance of these three algorithms is analyzed. They were selected because of their simplicity and popularity. In the case of P&O and InCond some modifications are proposed, which overcome the limitations of the original methods in tracking the MPP under irradiation slopes. The FLC is designed according to the references and its dynamic efficiency is tested and compared to the hill-climbing MPPT methods.

CHAPTER IV

Simulation and Realization of the system

Chapter IV

Simulation and Realization of the system

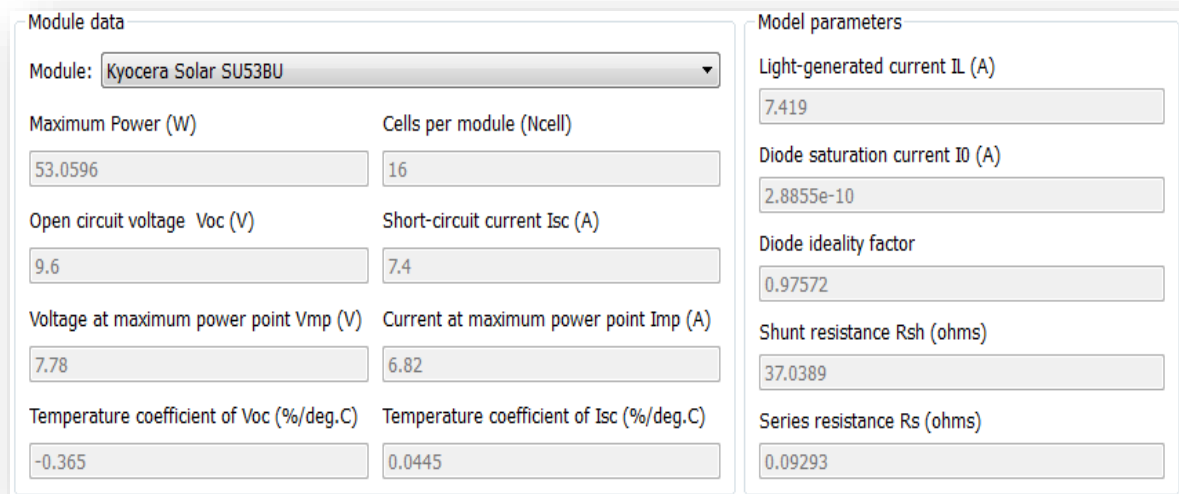
IV.1 Introduction:

The first part of this chapter is the simulation of the PV system ,the use of simulation is a very important step in the study of PV systems, it makes it possible to modify the parameters of the system very easily and to test the performance of the MPPT methods under different conditions and we tested four different method which are P&O ,InC ,Fuzzy logic and PSO based PID .

In the second part is the implementation of same sytem at real time, the system includes a photovoltaic panel, a DC-DC converter (Booster), an Arduino Mega 2560 board which used to control the converter, a resistive load, current and voltage sensors and an LCD display to display the results in real time .

IV.2 Simulation of the system:

To verify the performance of the proposed algorithms (P&O, INC, Fuzzy logic, PSO-PID), the simulation of the PV system shown in Figure IV.2 are developed and implemented in MATLAB/Simulink® software. The PV array consists of one PV module (Kyocera Solar SU53BU) of 53W as shown in Figure IV.1 with the current-voltage and power-voltage characteristics of the PV module illustrated in Figure I.6 and Table IV.1 is parameters list of the boost converter components.



Module data		Model parameters
Module:	Kyocera Solar SU53BU	Light-generated current I_L (A)
Maximum Power (W)	53.0596	7.419
Cells per module (Ncell)	16	Diode saturation current I_0 (A)
Open circuit voltage V_{oc} (V)	9.6	2.8855e-10
Short-circuit current I_{sc} (A)	7.4	Diode ideality factor
Voltage at maximum power point V_{mp} (V)	7.78	0.97572
Current at maximum power point I_{mp} (A)	6.82	Shunt resistance R_{sh} (ohms)
Temperature coefficient of V_{oc} (%/deg.C)	-0.365	37.0389
Temperature coefficient of I_{sc} (%/deg.C)	0.0445	Series resistance R_s (ohms)
		0.09293

Figure IV. 1:Electrical characteristics data of PV module taken from Matlab/Simulink

Boost converter	values
Input capacitance (C _{in})	4000 μ F
Inductance (L)	0.1 mH
Capacitance (C)	50 μ F
Load resistive (R)	15 Ω

Table IV. 1:: Parameters of the boost converter.

IV.2.2 Schema simulink of the system

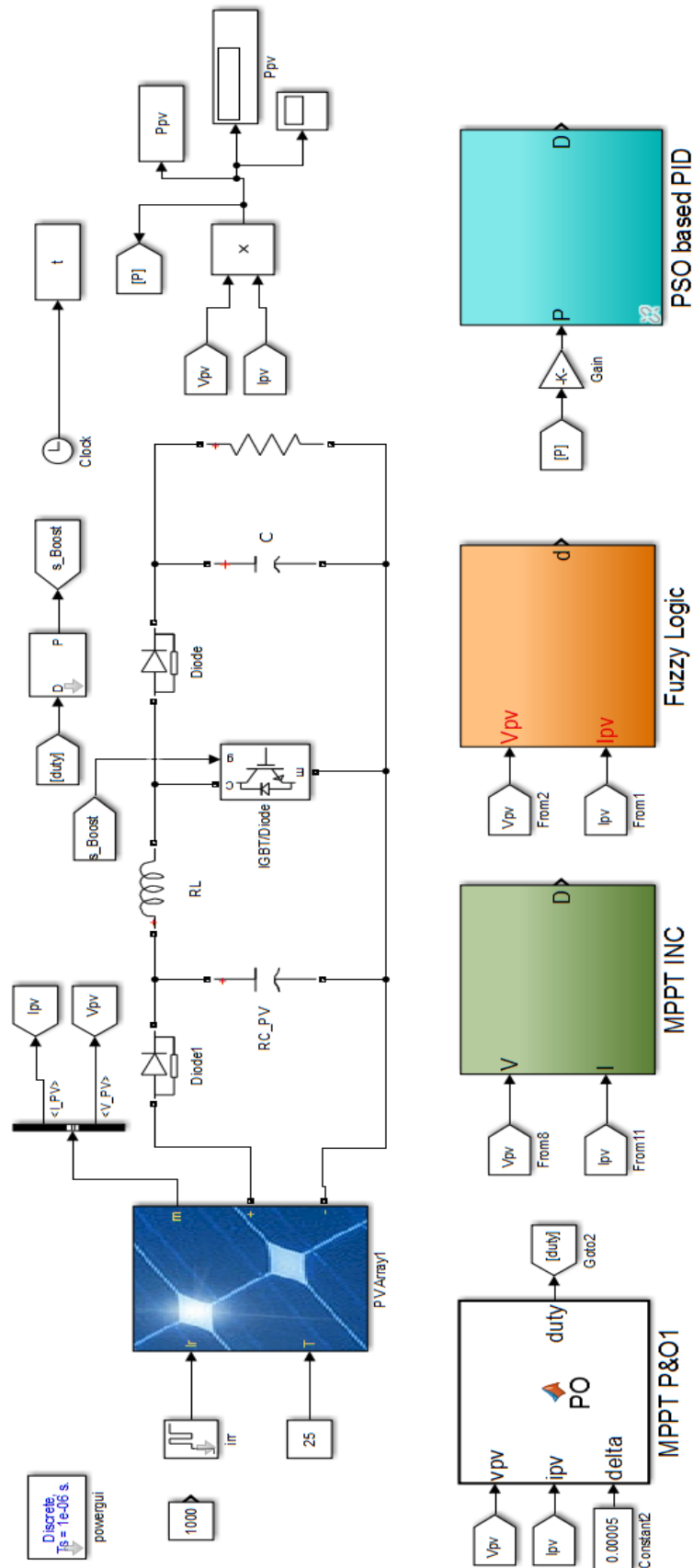


Figure IV. 2: Scheme MATLAB-SIMULINK of the system Photovoltaic with the studied methods of MPPT.

IV.2.3 Simulation results:

In this part, a comparative simulation analysis is performed to show the performance of the proposed MPPT algorithms, the simulation studies were carried out under steady-state and dynamic conditions by configuring the simulations under exactly the same weather conditions figure (IV.3).

The main focus is how fast the MPP is being tracked during the dynamic state and the power ripple caused by oscillations around the MPP in the steady-state condition.

From figure (IV.4), we see that the P&O algorithm with a fixed step of 0.005 shows a good dynamic performance compared to the P&O of 0.00005 which has drifting problem, it can converge more quickly towards the stationary state but the oscillation in static state is much higher. It takes 0.4 s to reach the MPP, while the P&O with a step of 0.005 takes 1.2 s to reach the MPP as shown in figure (IV.4) , the dynamic performance of P&O algorithm can be further improved by a larger step. However, this will have a negative effect on the steady-state performance.

The comparison between PID and PSO based PID is shown in Figure IV.5 .Clearly, the tracked power by PSO-PID shows high performance vs PID alone .the three parameters K_p , K_i and K_d of PID controller are tuned optimally by using PSO algorithm, the parameters used to initialize the PSO algorithm and generating an initial random population of individuals representing the PID controller gains (K_p , K_i and K_d) are defined in Table IV.2. the optimum PID controller gains are given after 20 hours of simulation in Table IV.3.

Description	Parameters
Population size	40
Maximum iteration	200
C1 and C2	1.2

Table IV. 2:PSO parameters

Gain	Value
K_p	328.0728
K_i	0.0100
K_d	0

Table IV. 3 : PSO Results.

In figure IV.6 the performance of the fuzzy logic and pso-PID shows excellent performance in the steady-state than P&O and Inc, they both has the ability to reduce the disturbed voltage when the MPP has been recognized , however in dynamic-state fuzzy logic is faster than all.

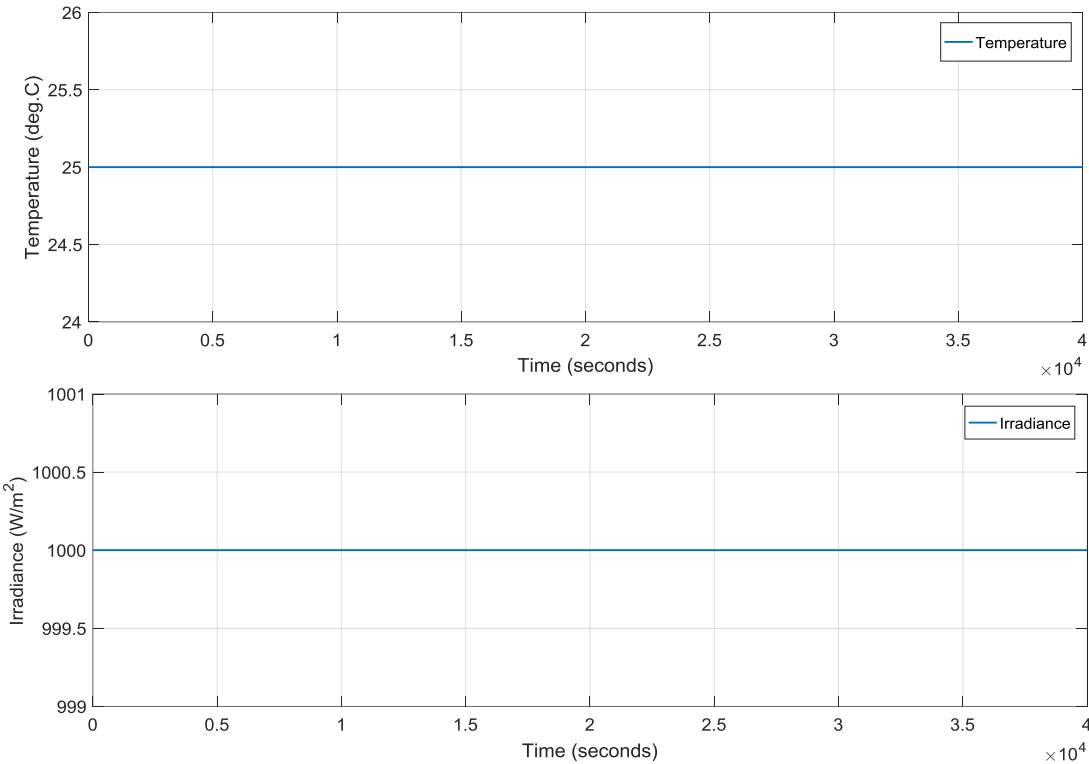


Figure IV. 3:The input of Temperature and Irradiance under constant conditions.

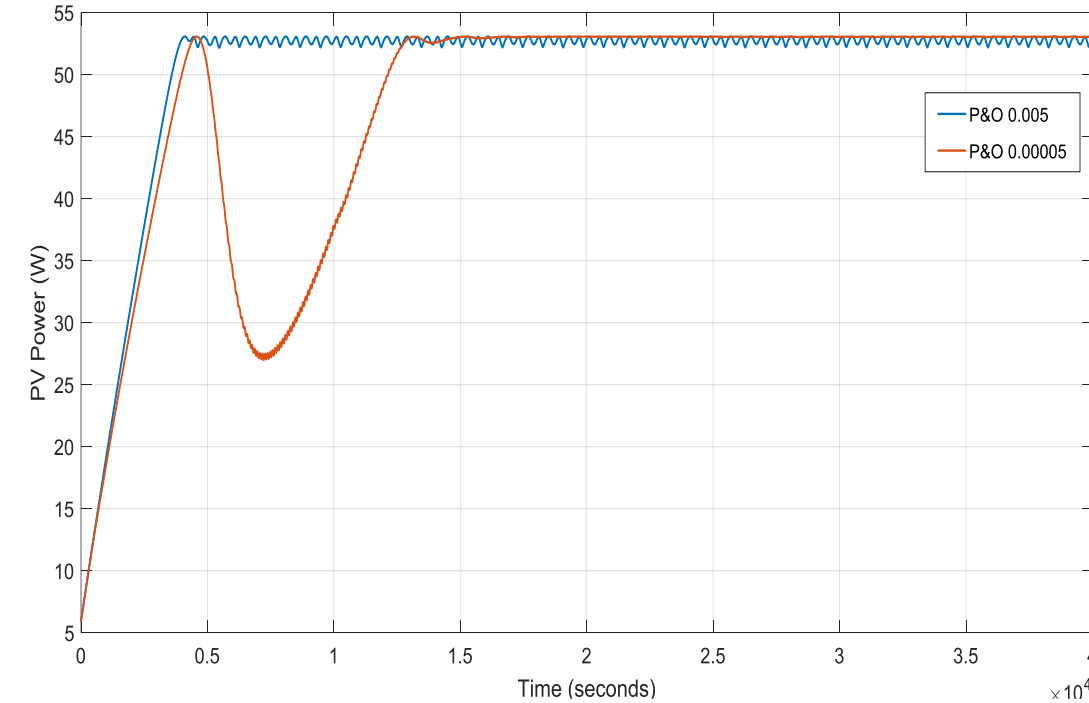


Figure IV. 4: PV power output using P&O algorithm with fixed step size of 0.005 and 0.00005.

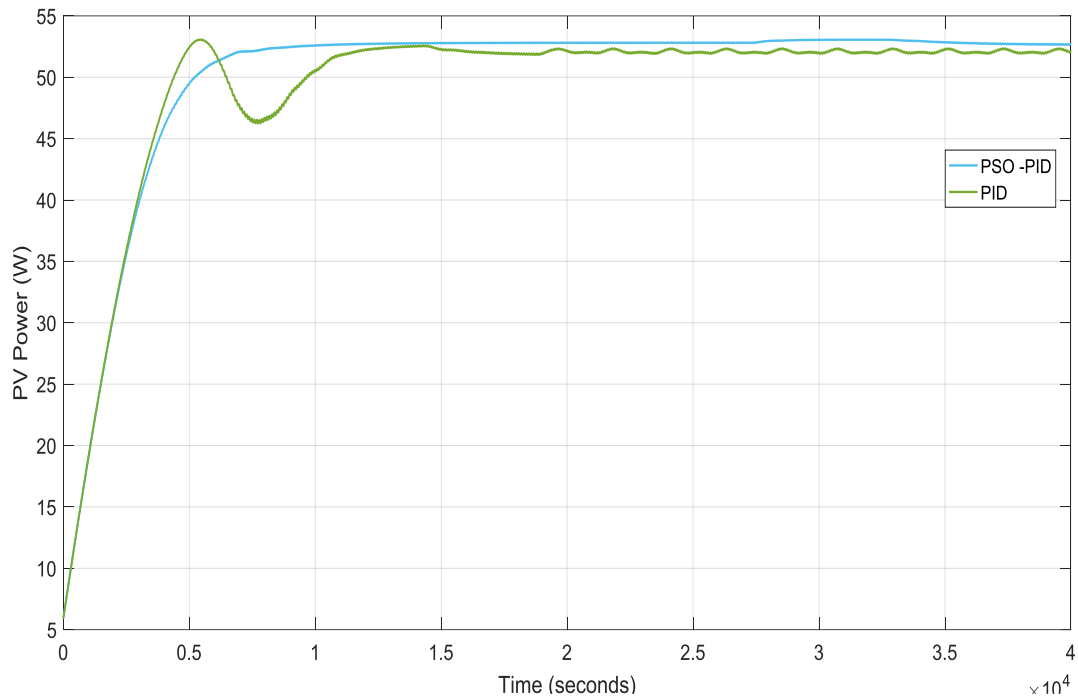


Figure IV. 5: PV power output using PID and PSO-PID.

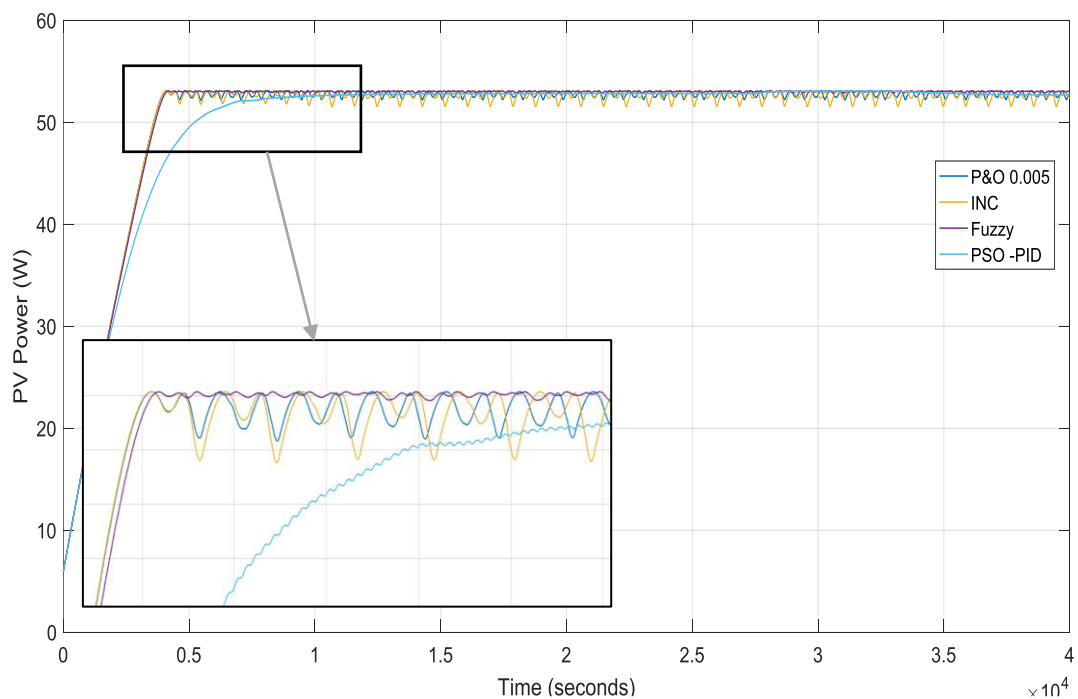


Figure IV. 6: PV power output of all proposed methods .

IV.3 Realization of the system:

In this part, an efficient maximum power point tracking system based on arduino /matlab using a real photovoltaic panel is designed. We will present the experimental results for the experiment , we had technical difficulties in implementing of Fuzzy Logic and PSO-PID in this part, so we had to remove both methods and work with P&O and INC only.

we did a real measurement test of cloudy day, sunny day and fake shaded panel to evaluate the efficiency of the proposed method under varying climate conditions.

MPPT control and data display using Arduino are very common, and we find lots of tutorials on websites. But, we haven't figured out how to do this using Matlab / Simulink. MathWorks got a very good support package for Arduino, but only for digital and analog pins. So far, they haven't released any support for LCD screens and signal acquisition through current and voltage sensors. Here in this work we will describe how to work with LCD screen using Arduino Mega and Simulink. The user does not need to do any programming in Arduino IDE. Everything will be done in Simulink using S_function builder. This solution consists on the one hand in using the functions offered by Simulink which makes it possible to send and acquire data via the serial port (USB) and on the other hand to process and visualize this data in real time.

Also, we did needed to make arduino PWM output reach to 20 kHz at least because arduino has limit to 1kHz with the help of special S-function code.

The block diagram is represented by figure IV.7

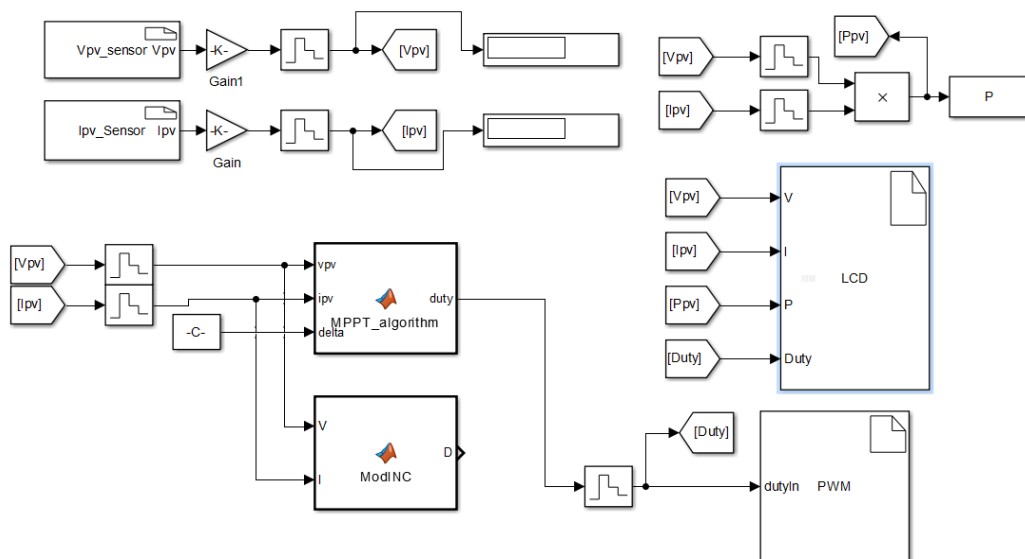


Figure IV. 7: Block diagram of acquisition, processing, control and real-time visualization of experimental results

Figure (IV.8) illustrates the complete project:

- 1- Hardware input, where the sensors of V_{pv} and I_{pv} will be read using arduino,
- 2- Data processing: by one of two MPPT algorithms and transfer the control signal to the Boost converter by the PWM_ converter ,
- 3- Hardware output, the processed data will be displayed on the LCD display ,
- 4- Visualization of curves, using "to work space" block.

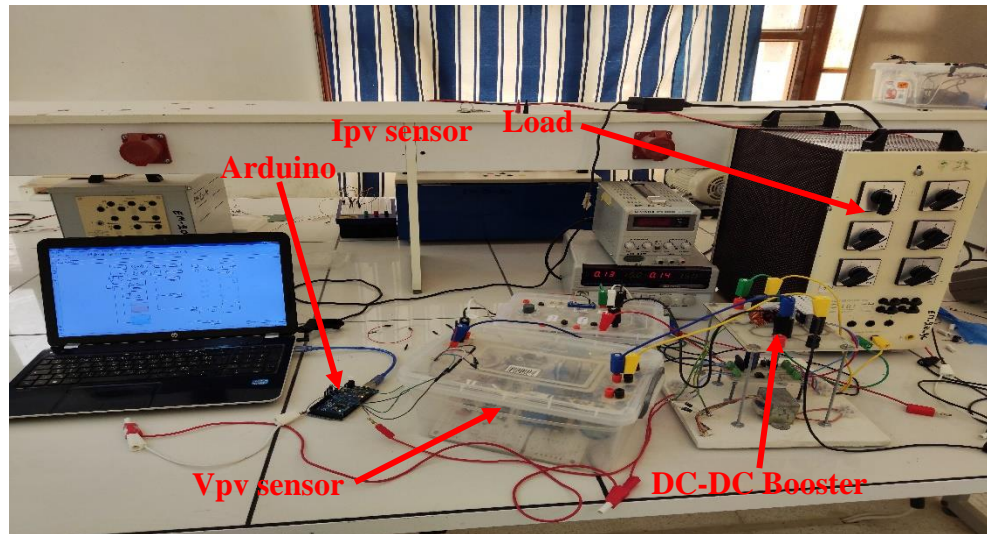


Figure IV. 8: Diagram of the realized photovoltaic system







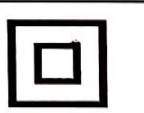
 	
Réf:5150-003 Electrical Characteristics	
Module Type :	50M(36)
Maximum Power :	50W(WP)
Tolerance :	±3%
Voltage at Pmax(Vmp):	17.98V
Current at Pmax(Imp):	2.78A
Open- circuit Voltage(VOC):	21.87V
Short-circuit Current(ISC):	3.04A
Size: 830*540*28MM Weight: 6 KG Cells: 36Pcs, 156*63 Monocrystalline silicon Max. System Operating Voltage: 1000(V) Maximum over-current protection rating: 10A Module Addication: Class A Standard Test Condition: 1000W/m², AM1.5, 25°C	
 WARNING! ELECTRICAL HAZARD This unit produces electrical power when exposed to light. Cover glass before opening terminal junction box.	
   	

Figure IV. 9: characteristics data of used PV module

IV.3.1 Experimental Results:

The experimental results of two algorithms previously studied are given by figures (IV.10), IV.11) and (IV.12).

The results show that the two MPPT algorithms exhibit good ability to track MPP and increase the performance of the PV system when a rapid change in irradiation occurs

P&O algorithm shows better performance in suny/cloudy day case however in fake shaded panel case INC shows better performance then P&O

The control by the two algorithms adapts the PV generator to the load by transferring the maximum power supplied by the GPV.

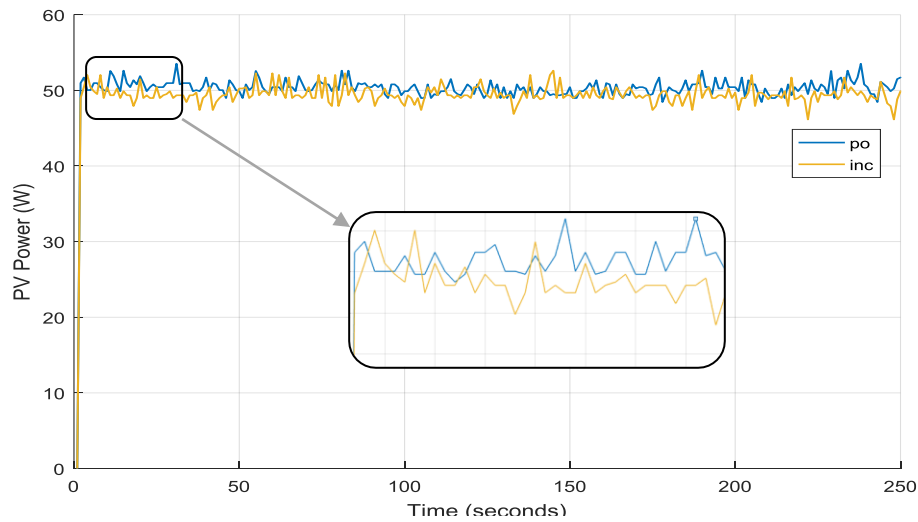


Figure IV. 10: Practical results of sunny day

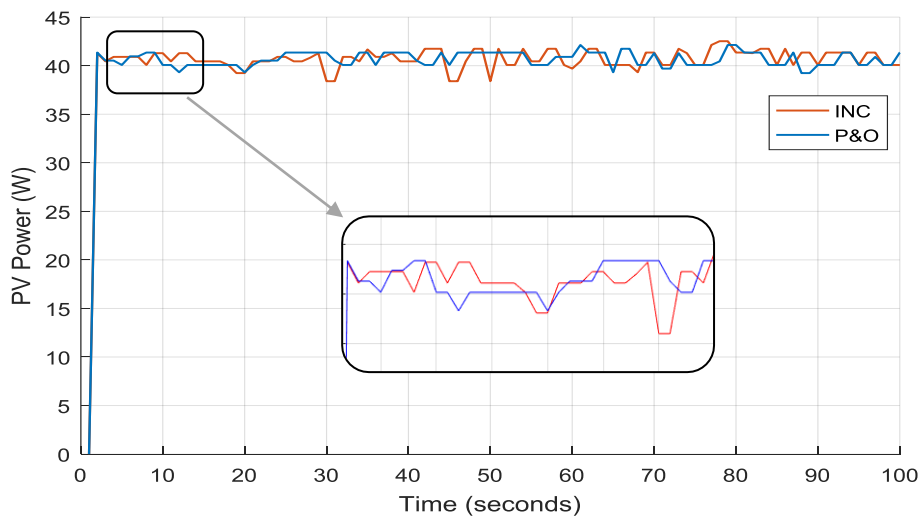


Figure IV. 11: Practical results of cloudy day.

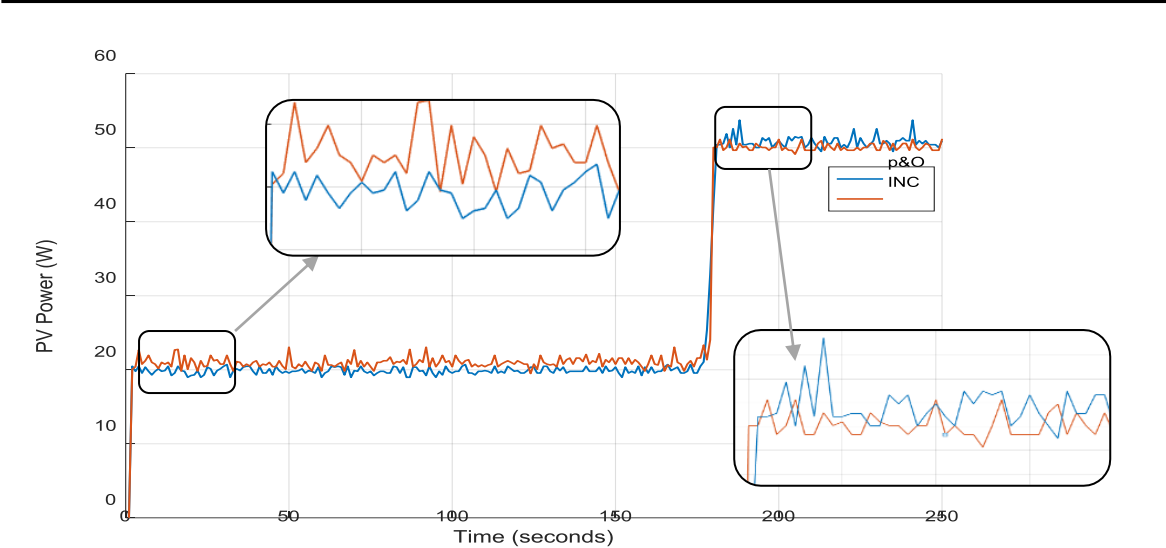


Figure IV. 12: Practical results of shaded panel.

Sunny day results	
Cloudy day results	
Shaded panel results	

Table IV. 3:: Display of practical results on LCD display.

IV.4 conclusion:

This chapter is devoted to the installation and simulation under matlab/simulink of a PV system, we controlled the system by diffrents types of MPPT algorithms, It can be concluded that with the propsted MPPT algorithms, the PV panel can provide the maximum power as shown in experimental results both P&O and INC has close results However, in simulation results the performance of the fuzzy logic and pso-PID is better than that of traditional algorithms , it has the ability to reduce the disturbed voltage when the MPP has been recognized. This action directly preserves more stable output power compared to conventional MPPT where the output power fluctuates around MPP.

General conclusion

The work presented in this thesis deals with the simulation, and implementation of a photovoltaic system operating with a BOOST converter. This converter has the advantage of being a voltage booster which allows this system to adapt to changes in weather and to extract the maximum power available to the load.

The simulation and experimental results have demonstrated the interest of a device for researching maximum power. The algorithms, P&O and INC are chosen to be implemented in an Arduino Mega2560 board, in order to track the operating point at maximum power of the PV panel.

From the simulation and experimental results, it can be concluded that with the proposer algorithms, the PV panel can deliver the maximum power. However, Although we could not actually implement them ,the performance of the fuzzy logic and PSO-PID is more robust, and more accurate than that of the (P&O) and INC, it has the ability to reduce the disturbed power when the MPP has been recognized.

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Appendixs



Simulation and Realization of MPPT methods in photovoltaic system

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Abstract

The electrical energy produced by photovoltaic (PV) process is inexhaustible, developable everywhere and clean. Whatever the conditions, it is desirable to extract the biggest amount of power from the solar panel. This is achieved with the use of a Maximum Power Point Tracking (MPPT) algorithm depending on environmental factors such as solar irradiance and ambient temperature.

Problem formulation

Fluctuations in weather conditions (irradiation and temperature) strongly degrade the performance of the photovoltaic module's energy conversion and therefore all the power can not be transferred to the load.

Proposed method

Perturb and Observe Method :

The P&O method is often used in photovoltaic systems. Based on the P-V characteristic, when PV power and voltage increase, a disturbance will add a step size ΔD with the duty cycle D , to create a subsequent disturbance cycle and move the working point moving to MPP. With the chance that the PV power decreases and the PV voltage increases, the algorithm works in the opposite way until the algorithm reaches MPP.

Incremental conductance Method :

The incremental conductance algorithm detects the slope of the P-V curve, and the MPP is tracked by searching the peak of the P-V curve. This algorithm uses the instantaneous conductance I/V and the incremental conductance dI/dV for MPPT. Depending on the relationship between the two values

Solution

A photovoltaic system mainly consists of a PV panel, a DC-DC adaptation stage with a MPPT algorithm and a load as represented by Figure 1.

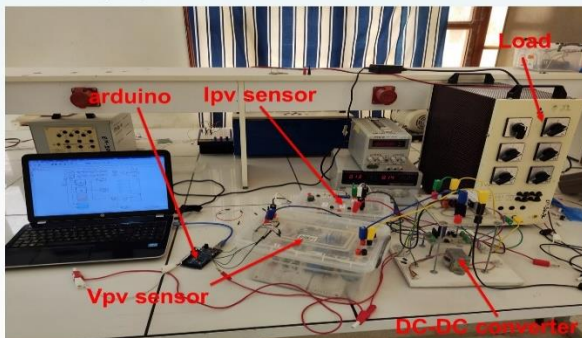


Figure 1: Proposed system Diagram.

we have design and implementation of our system with the two algorithms based on an Arduino Mega 2560 board and matlab as shown in Figure 2

Conclusion

This work gives an analysis of two widely used MPPT algorithms under variable atmospheric conditions of temperature and irradiation. These two MPPT methods are compared based on efficiency and response time. Both algorithms shows perfect efficiency and response time in steady as well as in dynamic conditions of weather

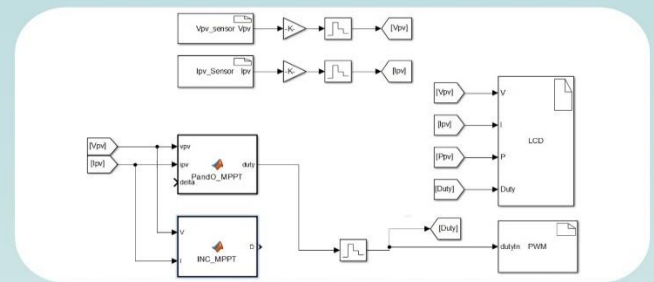
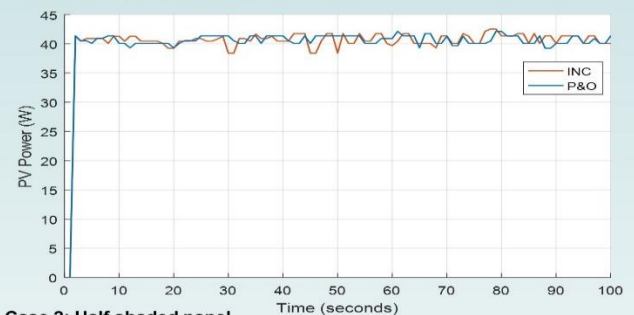


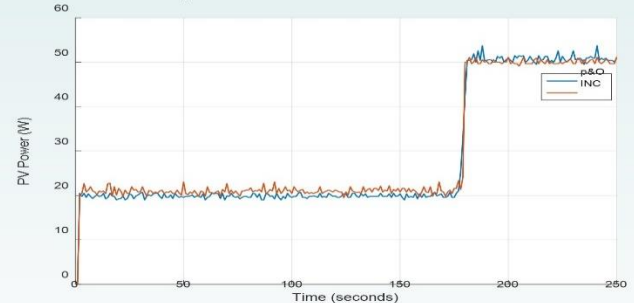
Figure 2: Proposed system

Results

Case 1: cloudy day 18/05/2021 11:00 AM



Case 2: Half shaded panel



Case 3 : Sunny day 09/06/2021 11:30 AM

