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Faculté des Sciences et de la Technologie
قسم الآلية و الكهرو ميكانيك
Département d'automatique
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Étude et Optimisation d'une centrale PV connectée au réseau électrique

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Faculty of Sciences and Technology

قسم الآلية والكهروميكانيك

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Study and Optimization of a PV Power Plant Connected to the Electricity Grid

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الملخص

تشهد أنظمة الطاقة الكهروضوئية (PV) حاليًا، سواءً المتصلة بالشبكة أو غير المتصلة بها، نموًا سنويًا متسارعًا، لتصبح جزءًا حيويًا من المشهد العالمي للطاقة. ومع ذلك، يتأثر أداء هذه الأنظمة بشكل كبير بالظروف الجوية، وخاصةً تقلبات الإشعاع الشمسي وارتفاع درجات حرارة الخلايا الشمسية. تقدم هذه الدراسة نمذجة ومحاكاة نظام توليد طاقة كهروضوئية متصل بالشبكة دون استخدام بطاريات، مُنفذ باستخدام Simulink/MATLAB الهدف الرئيسي هو تحسين أداء أنظمة الطاقة الشمسية من خلال استراتيجية تحكم قائمة على تتبع نقطة القدرة القصوى (MPPT)، باستخدام خوارزمية الاضطراب والمراقبة (O&P)، للحفاظ على التشغيل الأمثل بغض النظر عن تقلبات الطقس. يتم ربط مصفوفة الطاقة الكهروضوئية في البداية بمحول تعزيز تيار مستمر-تيار مستمر، ثم يتم توصيلها بشبكة التيار المتردد من خلال عاكس تيار مستمر/تيار متردد. ينظم العاكس الطاقة الفعالة والتفاعلية لتحقيق معامل قدرة واحد عند نقطة توصيل الشبكة، مع الحفاظ على تزامن الطور باستخدام حلقة قفل الطور (PLL). تؤكد نتائج المحاكاة فعالية نهج التحكم المقترح في إدارة تدفق الطاقة، مما يضمن إيصال أقصى طاقة ممكنة إلى الشبكة الكهربائية بكفاءة.

كلمات مفتاحية: نظام الطاقة الكهروضوئية المتصل بالشبكة، حلقة مقفلة الطور، مستمر/تيار متردد
محول تيار P&O

Abstract

Currently, both on-grid and off-grid photovoltaic (PV) power systems are experiencing rapid annual growth, becoming a vital part of the global energy landscape. However, their performance is significantly influenced by weather conditions—particularly fluctuations in solar irradiance and elevated solar cell temperatures. This study presents the modeling and simulation of a grid-connected PV power generation system without the use of batteries, implemented in MATLAB/Simulink. The primary objective is to enhance the performance of solar energy systems through a control strategy based on Maximum Power Point Tracking (MPPT), utilizing the Perturb and Observe (P&O) algorithm, to maintain optimal operation regardless of whether variability. The PV array is initially connected to a DC-DC boost converter and subsequently connected to the AC grid through a DC/AC inverter. The inverter regulates both active and reactive power to achieve a unity power factor at the grid connection point, while phase synchronization is maintained using a Phase-Locked Loop (PLL).Simulation results confirm the effectiveness of the proposed control approach in managing power flow, ensuring the efficient delivery of maximum power to the electrical grid.

KEYWORDS: Grid-connected PV system, Phase-Locked Loop, P&O, DC/AC inverter

Résumé

Actuellement, les systèmes photovoltaïques (PV), qu'ils soient connectés au réseau ou autonomes, connaissent une croissance rapide et constante, s'imposant comme un élément essentiel du paysage énergétique mondial. Toutefois, leurs performances restent fortement influencées par les conditions météorologiques, notamment les variations de l'irradiance solaire et l'élévation de la température des cellules photovoltaïques. La présente étude porte sur la modélisation et la simulation d'un système de production d'énergie photovoltaïque connecté au réseau et dépourvu de stockage d'énergie, développé sous MATLAB/Simulink. L'objectif principal est d'optimiser les performances du système à travers une stratégie de commande basée sur le suivi du point de puissance maximale (MPPT), mise en œuvre via l'algorithme de Perturbation et Observation (P&O). Cette approche permet de maintenir un fonctionnement optimal du système, quelles que soient les fluctuations climatiques. Le générateur PV est relié au réseau électrique à travers une chaîne de conversion en deux étapes : un convertisseur élévateur de tension (boost) de type DC-DC, suivi d'un onduleur DC-AC. L'onduleur assure la régulation des puissances active et réactive, afin de garantir un facteur de puissance unitaire au point de couplage réseau. La synchronisation avec le réseau est assurée par une boucle à verrouillage de phase (PLL), permettant d'aligner la phase de l'onduleur sur celle du réseau. Les résultats de simulation confirment l'efficacité de la stratégie de commande proposée, en démontrant sa capacité à gérer efficacement les flux de puissance et à assurer la livraison continue de la puissance maximale vers le réseau électrique.

Mots-clés : Système PV connecté au réseau, Boucle à verrouillage de phase (PLL), Perturbation et Observation (P&O), Onduleur DC/AC

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List of notations and abbreviations

	Designation
G	Solar radiation (W/m²).
I_0	Diode saturation Current (A).
I_{ph}	Cell photocurrent (A).
$I_{ph, ref}$	Cell referance photocurrent (A)
I_{max}	Maximum current cell (A).
Isc	Solar panel short circuit current (A).
E_g	Band gap energy of the material (1.12 eV for silicon).
S	PV Generator area [m²].
FF	Fill factor
N_s	Number of panels in series.
N_p	Number of panels in parallel
V_{PV}	Photovoltaic generator voltage
I_{PV}	Photovoltaic generator current. (A)
P_0	Incident power on the photovoltaic generator
i_L	Converter current DC/DC.
C_{PV}	Converter Capacity DC/DC.
R_S	Series resistance (Ω).
T	Cell temperature (°K).
T_{ref}	Reference cell temperature (°K).
V_{oc}	Solar panel Open current voltage (V).
K	Boltzmann Constant $1.38*^{10\text{-}23}$ J/K.
N	Diode quality factor
μ_{Isc}	Short circuit current temperature coefficient (A/°C)
μ_{oc}	Temperature coefficient of open circuit current (V/°C).
P_{PV}	Power of photovoltaic generator(W)
q	Electron charge constant, $1.602\ x\ 10^{-19}$ C.

Liste of abbreviations

PV	Photovoltaic
PVG	Photovoltaic Generator
Pmax	Maximum Power

List of notations and abbreviations

P_0	Incident Power
η	Solar Efficiency
Rs	Series resistance
Rp	Parallel resistance
T	Ambient temperature in K
T_{ref}	Absolute temperature in K
I_{sh}	Current through resistor R_{sh}
V_{CO}	Open-circuit voltage
A	Cell ideality factor
I_{sc}	Short-circuit current
I_M	Optimal current
Ns	Number of cells in series
Np	Number of cells in parallel
FF	Form factor
V_M	Maximum voltage
I_M	Maximum current
AC	Alternating current
DC	Direct current
Vin	Inverter voltage
Vdg	Direct Grid voltage
Vqg	Quadratic Grid voltage
VL	Inductor voltage
Vpv	Photovoltaic panel voltage
Ipv	Photovoltaic panel current
m_f	Frequency modulation index

List of notations and abbreviations

m_a	Amplitude modulation index
I_{ref}	Reference current
V_{ref}	Reference voltage
P_{ref}	Reference power
Q_{ref}	Reference reactive power
MPP	Maximum power point
MPPT	Maximum power point tracking
I_{grid}	Grid current
Grid	Electrical grid
R_{sh}	Shunt resistor (parallel)

General introduction

General introduction

Photovoltaic (PV) solar energy relies on the direct conversion of a portion of solar radiation into electricity, thanks to the photovoltaic effect, discovered in 1839 by Alexandre Edmond Becquerel. This effect allows the electrons present in the semiconductor materials of PV cells to become excited under the impact of photons, thus generating a direct current. These cells, assembled to form modules, are the basic element of a PV panel, whose main function is to transform light energy into electrical energy.

Increasingly, PV systems are being connected to the electricity grid, where the generated energy is directly injected into the grid, thus transforming solar installations into true "mini-power plants". However, this connection raises two major challenges: the stability of the grid in the face of fluctuations in photovoltaic production and the quality of the energy delivered at the connection point. To overcome this, it is necessary to have a suitable conversion system, generally comprising a DC-DC converter (boost) followed by an inverter, and this, with appropriate sizing and control.

The main problem of this work therefore lies in the design and optimization of an inverter control strategy, aimed at ensuring reliable interconnection with the grid, effective monitoring of the MPP and compliance with power quality standards. The objectives are as follows:

- Develop an efficient PV/Boost/Inverter conversion scheme.
- Implement a robust MPPT algorithm.
- Ensure stable and grid-compliant injection.

This thesis consists of four main chapters:

The first chapter presents a comprehensive state-of-the-art review of PV systems in a global and national context. It begins with an overview of global electricity production, with an emphasis on the growing share of renewable energy. The chapter then explores the different forms of renewable energy available in Algeria, including solar thermal energy and wind energy. Particular attention is paid to photovoltaic solar energy, detailing the principle of the photovoltaic effect, solar cell technologies (crystalline, thin-film, multi-junction), as well as their advantages, disadvantages and areas of application. Finally, protection elements of PV systems such as bypass and non-return diodes are presented, before concluding with a summary of the strengths and limitations of photovoltaic systems.

The second chapter is devoted to the modeling of the various components of a grid-connected photovoltaic (PV) system. It begins with a general overview of how such a system works, highlighting the importance of accurately representing the electrical characteristics of the photovoltaic generator. The impact of climatic conditions, such as sunshine and temperature, on the current-voltage (I-V) and power-voltage (P-V) curves is also studied, as are the effects of partial shading. Subsequently, the chapter deals with the modeling of the Boost type DC-DC converter, essential for voltage adaptation between the PV generator and the inverter. MPPT (Maximum Power Point Tracking) control is also discussed, with a summary of the main methods from the literature, and a detailed explanation of the Perturb and Observe (P&O) method. Finally, the chapter concludes with a presentation of the quality standards for grid-connected photovoltaic systems, ensuring their reliability, safety and performance.

The third chapter deals with the complex interactions between the inverter and the electrical grid in a grid-connected photovoltaic system. It begins with an overview of the operating principle of DC-AC converters (inverters), distinguishing between single-phase and three-phase configurations depending on the application. Inverter modeling is discussed to provide a detailed understanding of its dynamic behavior and its integration into the overall system. The chapter also covers DC bus voltage control, synchronization with the grid via the phase-locked loop (PLL), and grid-side control techniques, which ensure efficient and standard-compliant energy injection. All of these elements are crucial to ensure stability, the quality of the injected energy, and compatibility between photovoltaic production and the electrical grid.

Finally, the fourth chapter is dedicated to the simulation of a PVG connected to the electricity grid, using a suitable modeling environment such as MATLAB/Simulink. The main objective is to validate the theoretical models developed in the previous chapters and to evaluate the dynamic behavior of the system under different operating conditions. Through this simulation, it is possible to analyze the impact of variations in sunshine and temperature on photovoltaic production, to observe the operation of the DC-DC converter, as well as the MPPT control to optimize the power extracted from the generator. The simulation also allows for the study of inverter performance when injecting power into the grid, highlighting the interaction phenomena between the PV generator and the electrical grid. This work constitutes an essential step in validating the feasibility and efficiency of the system before any actual implementation.

In conclusion, this work provides a detailed analysis of the various facets of the grid-connected photovoltaic system, while opening up avenues for future improvements.

CHAPTER 1: STATE OF THE ART OF PHOTOVOLTAIC SYSTEMS

1.1. Introduction

In recent decades, the need to reduce dependence on fossil fuels and limit the environmental impacts associated with their use has led to growing interest in renewable energies. Among these, photovoltaic solar energy has quickly emerged as a promising, clean, and sustainable solution.

A photovoltaic (PV) system is a device that converts solar energy directly into electricity using solar cells. It can be used in stand-alone (off-grid) or grid-connected (on-grid) applications, and its design depends on many factors such as sunlight, panel technology, the type of converters used, and energy management strategies..

1.2. Global Electricity Production

The International Energy Agency's (IEA) central scenario projects that global electricity production will increase by more than 36% from 2012 to 2025.

Table 1.1: Global Electricity Production

Form of energies	**Request in 1990**	**Request in 2012**	**Request in 2025**
Annual production in TWh			
Coal	4 425	9 204	10 800
Oil	1 310	1 144	695
Natural gas	1 760	5 104	7 010
Nuclear	2 013	2 461	3 594
Hydro-electricity	2 144	3 672	5 004
Renewable	173	1 135	3 713
Total	**11 825**	**22 721**	**30 817**

Electricity consumption in developing countries is expected to continue its relatively pronounced growth, while it will be more modest and stable in the main OECD member countries (United States, Canada, Mexico and Chile).. Thus, the share of non-OECD countries (Asia and Africa) whose global demand will reach 60% in 2025, an increase of nine percentage points [1]. The majority of electricity produced in the world comes from the decomposition of fossil fuels (oil, coal or natural gas) or nuclear fuels (Figure 1.1) [2] [3].

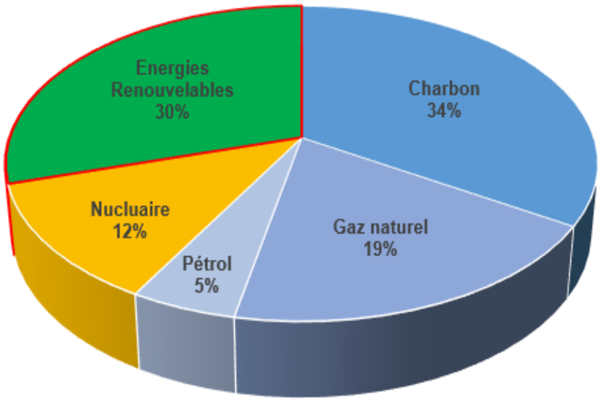


Fig.1.1. World electricity production

1.3. Production of electricity from renewable sources in the world

Thanks to technological advances, the electricity sector, the largest source of greenhouse gas emissions worldwide, has become a major target of efforts to combat climate change. In order to reduce the electricity sector's dependence on fossil fuels, several government policies encouraging or forcing the adoption of low-carbon generation sources have been implemented over the past decade. For example, the International Energy Agency (IEA) anticipates that, by 2025, the average annual growth in electricity generation from renewable sources will be four times higher than that of total electricity generation [4]. Renewable energy is energy produced from sources that can be renewed indefinitely, such as hydroelectric, solar and wind power, or produced sustainablyfrom biomass (Figure1.2).

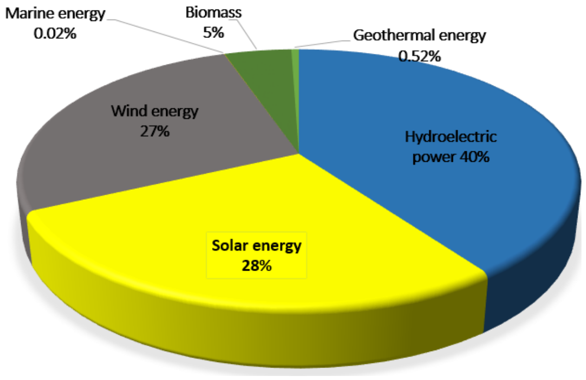


Fig.1.2. Production of electricity from renewable sources in the world

Renewable electricity comes from six distinct sources. Hydroelectricity (including pumped storage power plants) is the first of these with a contribution of 40% in 2023. Solar energy has become the second source of renewable energy (28%), which includes PV power plants and thermal power plants. It is ahead of the wind turbine sector (27%). Followed by biomass (5%), geothermal energy (0.52%) and marine energy (0.02%), which remains a sector in the demonstration phase [6].

Renewable electricity production has reached a high percentage worldwide, crossing the threshold of 30% of global electricity production. This share remains higher than electricity production from natural gas and nuclear sources. It can therefore be stated that renewable energies have, over the last decade, consolidated their place in the global structure of electricity production [7] [8].

1.4. Average annual growth rate of renewable sectors

Since 2005, the share of renewable energy has experienced continuous and significant growth, reaching 30.24% in 2023. This increase reflects increased efforts to combat climate change, technological advances in renewable energy, and favorable government policies. The post-2010 period particularly marked an acceleration of this trend, with a notable average annual increase, notably an increase from 18.71% in 2010 to 30.24% in 2023. Recent years have also seen significant increases, notably in 2020 when the share of renewables climbed to 28.08%, supported by increased global awareness of environmental issues and substantial investments in green infrastructure. These trends highlight a gradual but determined energy transition towards more sustainable energy sources.

Table 1.2: Share of renewable energy in electricity production (2012–2023)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Share of ER (%)	20,9 %	21,7 %	22,2 %	22,9 %	23,7 %	24,5 %	25,1 %	26,19 %	28,08 %	28,14 %	29,42 %	30,24 %

Renewable energy accounted for 19% of global electricity generation in 2000, compared to more than 30% in 2023. This is due to:

- The increase in Solar and wind energy, which rose from 0.2% in 2000 to a record level of 13.4% in 2023;
- In particular solar energy, at the forefront of the energy revolution with electricity production more than twice that of coal in 2023.

In 2023, for the second consecutive year, global growth in solar production (+307 TWh, +23%) outpaced that of wind power (+206 TWh, +9.8%). Fossil fuel production increased by only +0.8% over the year Furthermore, solar and wind power accounted for 98% of new renewable capacity installations worldwide.

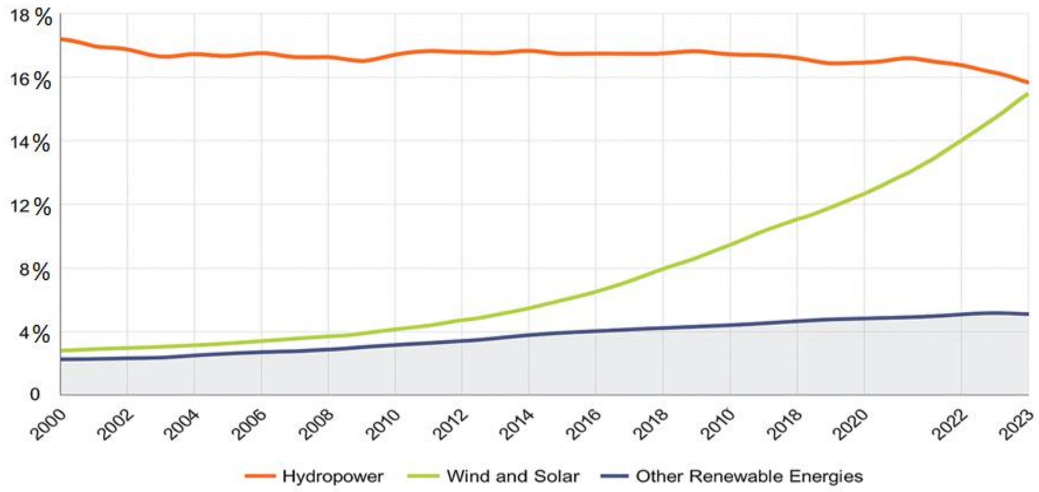


Fig.1.3. Average annual growth rate (%) 2000-2023[9]

1.5. Energy situation in Algeria

Through the launch of an ambitious program to develop renewable energies (RE) and energy efficiency, Algeria is initiating a green energy dynamic based on a strategy focused on the development of inexhaustible resources and their use to diversify sources energy and prepare the Algeria of tomorrow. Thus, Algeria is embarking on a new sustainable energy era [10]. Algerian energy policy has set the following objectives:

The development and conservation of hydrocarbon resources;

- The development of domestic use of natural gas;
- The development of renewable energies;
- Improving energy demand management; Le renforcement de l’efficacité énergétique.

1.6. Production of electricity from renewable sources in Algeria

In 2014, CO_2 emissions from fossil fuels were 122.93 Mt CO_2, or 3.16 tonnes per inhabitant, 29% lower than the world average: 4.47 tonnes, but 3.3 times the African average: 0.96 tonnes (France: 4.32; Tunisia: 1.57) [11]. According to the Algerian Renewable Energy and Energy Efficiency Development Program (PNEREE) of 2012, Algeria aims for an installed capacity of renewable origin of 22,000 MW by 2030, of which 12,000 MW will be dedicated to covering national electricity demand and 10,000 MW for export [12].

Le gouvernement algérien a adopté fin février 2015 son programme de développement des énergies renouvelables 2015-2030. Une première phase du programme, démarrée en 2011, avait permis la réalisation de projets pilotes et d'études sur le potentiel national. Le nouveau programme précise les objectifs d'installations d'ici à 2030 :

- 13,575 MWc of Solar PV;
- 5,010 MW of Wind power;
- 2,000 MW of solar thermal power (CSP);
- 1,000 MW of biomass (waste recovery);
- 400 MW of cogeneration;

- 15 MW of geothermal energy.

The total thus amounts to 22 GW. By 2030, 37% of installed capacity and 27% of electricity production for national consumption will be of renewable origin [13].

The Sonelgaz group has invested heavily in the renewable energy sector. As part of its renewable energy development program, the group plans to implement 67 solar power plant projects, including 27 photovoltaic power plants, 27 hybrid power plants, 6 solar thermal power plants, and 7 wind power plants [14].

Among these national projects that have been launched are the "Solar 1000" and "Solar 2000" projects.

Table (1.3): shows international and national calls for tenders for: study, engineering, civil engineering, supply, assembly, training, and commissioning of the Solar 1000 project.

Table 1.3: Solar 1000 project: PV power plants connected to the Algerian electricity grid.

	Grouping	**Power plant site**	**Power (MW)**	**Cost (Md DA)**
1	AMMIMER ENERGIE SPA	Beni ounif (Bechar)	50	5.18
2	AMMIMER ENERGIE SPA	Ain beida (Ouergla)	100	9.34
3	GROUPE OZGUN/ BOU-ZIDA	Hassi delaa (6)	300	24.56
4	CHINA STATE CONSTRUC-TION	Foulia (Eloued)	300	28.33
5	Eurl Hamdi	Tamacine (Touggort)	250	20.56
		Total	**1000**	**87.97**

Sonelgaz Renewable Energies (Sonelgz-EnR) recently announced the award of international contracts within the framework of the 2000 MW solar PV energy project, which consists of the construction of fifteen (15) solar PV power plants, across 12 states, with a unit power, which varies between 80 and 220 MW. The total cost of the

Solar 2000 project is estimated at over 171 billion dinars (approximately $1.2 billion), with a completion time ranging from seven to 16 months. The project is expected to generate 10,000 jobs. It is worth noting the strong presence of Chinese companies, which have been awarded the construction of most of the photovoltaic solar power plants. The Chinese participation in the project is made up of 2 groups and 3 companies which will build a total of nine (09) power plants out of the 14 planned for an amount of more than 119 billion dinars, or 70% of the project.

Thus, the construction of five solar PV power plants with a capacity ranging from 80 MW to 220 MW was awarded to the Chinese consortium CWE-HXCC-YRED.

Table 1.4: Solar Project 2000 awarded to the Chinese consortium CWE-HXCC-YRED

	Power plant site	**Power (MW)**	**Cost (Md DA)**
1	Batmet (M'sila)	220	17.96
2	Gueltet Sidi Saad (Laghouat)	200	16.23
3	Douar El Maa (El Oued)	200	16.44
4	Ouled Djellal	80	7.31
5	Abadla (Béchar)	80	7.18
	Total	**780**	**65.12**

Other consortiums and companies (Chinese, Turkish, and Algerian) were also awarded the construction of nine large solar power plants.

Table 1.5: Remainder of the 2000 Solar Project allocated to other Consortiums (Chinese, Turkish, and Algerian)

	Grouping	Power plant site	Power (MW)	Cost (Md DA)
1	Shanxi Installation Group ltd	Ouled Fadel (Batna)	80	7.8
2	CSCEC	Tendla (El M'ghaier)	200	15.76
3	PowerChina NTL-SinoHydro	Laghrous (Biskra)	200	18.13
4	PowerChina Eng Corporation Limited	Khanguet Sidi Nadji (Biskra)	150	12.8
5	PowerChina Zhongnan Eng.	Kenadsa (Béchar)	120	11.85
6	CSCEC	Touggourt	150	14.47
7	Groupement Ozgun Insaat-Zergoun	Guerrara (Ghardaïa)	80	9.62
8	Eurl Hamdi	El Euche (Bordj Bou Arréridj)	80	8.03
9	Eurl Hamdi	Taleb Larbi (El Oued)	80	8.04
		Total	**1140**	**106.5**

Construction of the solar power plants began in January 2024. Most companies have completed the civil engineering work, leaving only the electrical work (PV panels, cabinets and transformers).

1-7. Solar potential in Algeria

In Algeria, PV energy is one of the national priorities for a successful energy transition. Thanks to its unique geographical location and abundant natural resources, Algeria has enormous solar potential, ranking it among the countries most exposed to solar radiation in the world, with an average of more than 3,000 hours of sunshine per year, particularly in desert regions. With an average sunshine rate of 6.57 kWh/m2/day, almost the entire national territory benefits from more than 2,000 hours of sunshine per year, including 3,700 hours in the Sahara. The table below presents Algeria's solar potential in figures and by location.

Table 1.6: Solar potential in Algeria

	Coastal regions	**Highlands**	**Sahara**
Superficie %	4	10	86
Average sunshine duration (h/year)	2650	3000	3500
Average energy received (kWh/m²/year)	1700	1900	2650

1.8. Energy efficiency program in Algeria

The goal of energy efficiency is to produce the same goods or services, but using as little energy as possible. The basic elements of this strategy include a national energy efficiency program supported by a national fund. This program should help to avoid CO_2 emissions. The energy efficiency action plan is as follows: [15]

- Thermal insulation of buildings;
- Development of solar water heaters;
- Widespread use of low-energy light bulbs;
- Introduction of energy efficiency in public lighting;
- Promotion of energy efficiency in the industrial sector.

1.9. Solar PV

The objective is to achieve an integration rate of 80% of Algerian capacity between 2015 and 2025. To achieve this, the construction of a PV module manufacturing plant is planned (Ouargla, Sidi Belabes and Bordj Bou Arreridj).

Furthermore, it is expected that a national subcontracting network and a solar equipment approval center will be set up for the manufacture of inverters, batteries, transformers, cables and other equipment used in the construction of a PV power plant: [16].

1.10. Solar thermal

Algeria plans to launch projects for the local manufacturing of solar thermal equipment. A 50% integration rate is expected through the implementation of three major projects that will be carried out in parallel with engineering capacity building initiatives:

- Construction of a mirror manufacturing plant;
- Construction of energy storage equipment;
- Development of solar thermal power plant construction capacity;

1.11. Wind power

Algeria aims to develop its manufacturing capacity for wind turbine masts and rotors and the development of a national subcontracting network for the manufacture of nacelle equipment.

The project also includes the design, procurement and construction of wind turbines, as well as the management of engineering, procurement and construction activities for power plants and brackish water desalination units. This period will be marked by the following actions:

- Construction of a wind turbine mast and rotor manufacturing plant;
- Creation of a national subcontracting network for the manufacturing of nacelle equipment;
- Enhanced engineering skills and design capabilities;
- Procurement and implementation capable of achieving an integration rate of at least 50% by Algerian companies.

1.12. Principle of the PV effect

A solar cell, also known as a solar cell or PV, is made from semiconductor materials. It can be thought of as a flat diode that is sensitive to light. A PV cell allows the direct conversion of light energy into electrical energy. A cell consists of two parts that are doped differently. The N layer has an excess of peripheral electrons doped with phosphorus and the P layer has a deficit of peripheral electrons doped with Bor. The two layers thus have a potential difference.

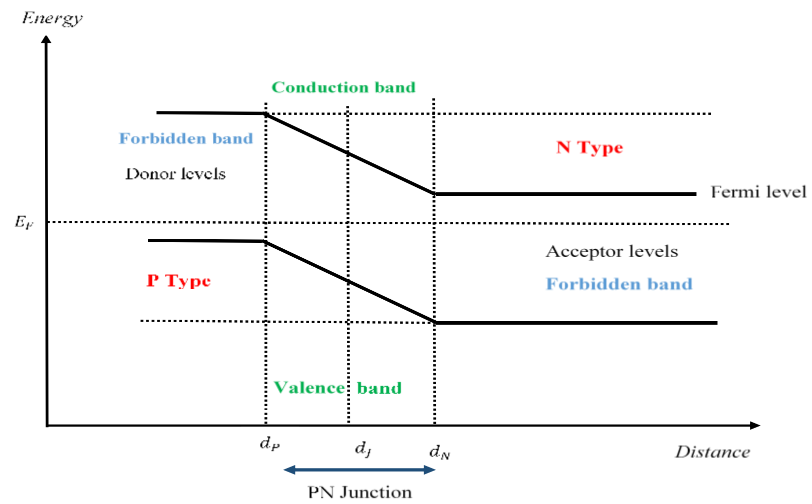


Fig.1.4. Energy band diagram near the junction

When this diode is exposed to photons whose energy (hv) is higher than the energy of the material, called the band gap energy (Eg), (Eg = EC -EV), the electron passes from the valence band to the conduction band leaving a hole behind it. The excess energy will be lost as heat and the electron will take a stable level in the conduction band. If the incident photons have with energy lower than Eg, they will not be absorbed, i.e. their energies do not contribute to photovoltaic conversion [17][18].

1.13. PV cell technologies

A PV cell can be made with many semiconductors. In reality, there are currently three types of solar cells depending on their production method: crystalline silicon, thin films and organic cells [19].

1.13.1. 1st generation technology: crystalline cells

First-generation cells are based on a single P-N junction that typically uses crystalline silicon as the semiconductor material. The production method is based on silicon wafers (thin slices). This method is very energy-intensive and therefore very expensive, and it also requires highly pure silicon. Crystalline silicon dominates the market by over 80%. This sector comprises two technologies: monocrystalline silicon and multicrystalline silicon [20].

- Monocrystalline silicon**:** This type of cell is made from a pure silicon crystal. The atoms are arranged in an orderly manner, which optimizes the efficiency of converting light into electricity. Monocrystalline cells are known for their high efficiency, generally between 18% and 22%, and exceptional durability (they can last more than 25 years).

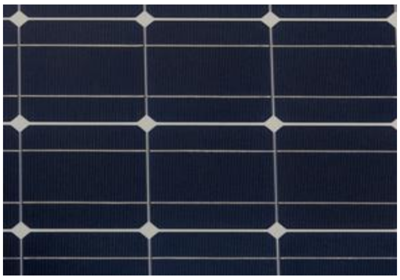


Figure 1.5. Monocrystalline cell

- Polycrystalline silicon: This type of cell is made from molten silicon. It is less expensive to produce than monocrystalline cells, but its efficiency is also lower, around 15% to 18%.

Figure 1.6. Polycrystalline cell

1.13.2. 2nd generation technology: thin films

In the case of "thin layers", the semiconductor is directly deposited by vaporization onto a support material (glass for example). There are several types of thin-film cells, namely:

- Amorphous silicon (a-Si).
- Cadmium telluride (CdTe).
- Copper/indium/selenium or copper/indium/gallium/selenium (CIS or CIGS).

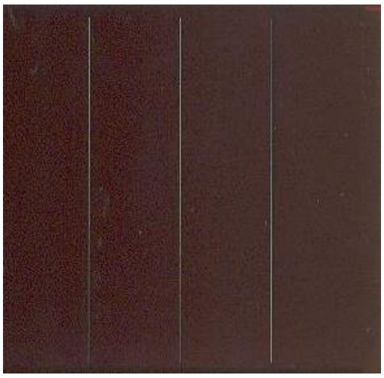


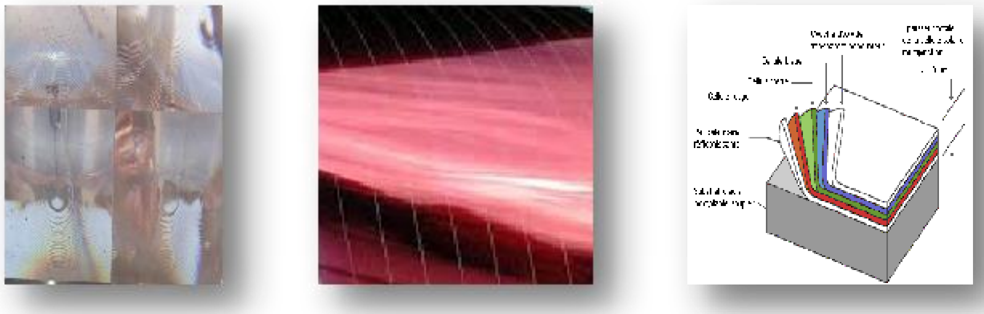
Figure.1.7. Thin-film cell

Its price is lower than crystalline cells; on the other hand, its efficiency is lower than that of crystalline cells, it is between 7% and 11%. They operate with low illumination and capture diffuse radiation very well. They are therefore less sensitive to variations in direct radiation, thus offering a very good alternative to crystalline cells on sites subject to severe shading.

1.13.3. 3rd generation technology: multijunction, concentration, multilayer

Third-generation solar cells, also known as dye-sensitized solar cells, are photovoltaic devices that use photosensitive materials to convert sunlight into electricity. Unlike traditional silicon-based solar cells, these solar cells use more advanced conversion mechanisms and innovative materials to improve their efficiency and performance. They are made of organic molecules that combine flexibility and lightness. There are three types of these cells:

- **Multilayer cells:** stacking multiple cells with different properties (using different energy bands, allowing for a broader scan of the solar spectrum).
- **Concentrating cells:** (allows the use of low-energy photons that are not normally absorbed by the cell). The efficiencies obtained under concentrating conditions are very promising (around 30%).
- **Organic cells:** are photovoltaic cells in which at least the active layer is made up of organic molecules. There are mainly organic photovoltaic cells and organic photovoltaic cells made from molecular polymers.



(a) Concentration cell (b) Organic cell (c) Multilayer cell

Fig.1.8. Multijunction and concentration cells

Table 1.7: Yield comparisons of different PV module technologies

Type	**Lab module**	**Commercial module**	**Level of development**
1st generation			
Mono-crystalline	26.1%	14-24%	Industrial production
Poly-cristalline	21.5%	13 -18%	Industrial production
2nd generation			
Amorphous (a-SI)	10.8%	6-9%	Industrial production
CdTe	22.1%	17.2%	Industrial production
Cis ou CIGS	22.3%	20.4%	Industrial production
3rd generation			
Concentrated	48.4%	39.7%	Industrial production
Multilayer	35%	29.9%	Industrial production for space applications
Multi-Junction	47.2%	32.1 %	Industrial production for space applications

1.14. Classification of PV Systems

There are three general types of photovoltaic systems: stand-alone systems, hybrid systems, and grid-connected systems. The first two are independent of the electricity distribution system, often found in remote areas.

1.14.1. Stand-alone PV systems

The role of autonomous systems is to supply one or more consumers located in an area isolated from the electricity network. The photovoltaic field see figure (1.9) can directly provide the electrical energy needed to operate the receivers (lighting and domestic equipment). A regulation system and a storage battery store electrical energy, which can then be used in the absence of the sun. Batteries are used to store electrical energy in chemical form. They release electrical energy as needed, depending on its characteristics. The main function of the charge regulator is to protect the battery from overcharging and deep discharge. It is an essential element for the battery's lifespan. In isolated locations, AC receivers can also be used. In this case, the installation will include an inverter.

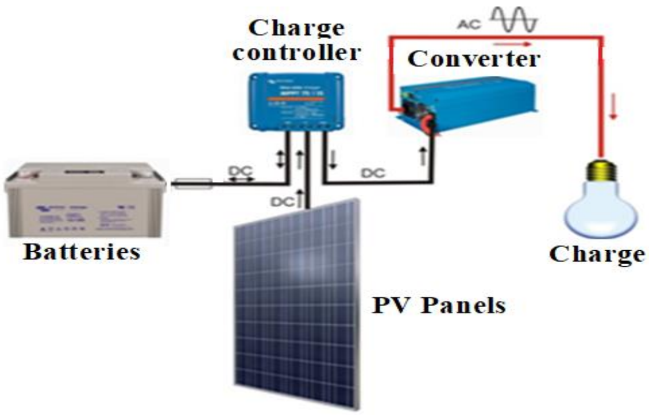


Figure 1.9. Typical diagram of a stand-alone PV installation [22]

1.14.2. Hybrid PV systems

These are systems that combine different energy sources, such as a wind turbine, a diesel generator, or a cogeneration plant in addition to the PVG. This type of installation is used when the PV generator alone does not cover all the required energy.

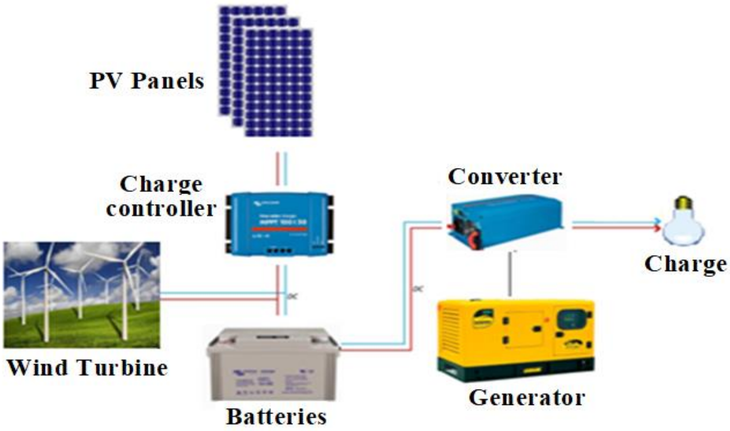
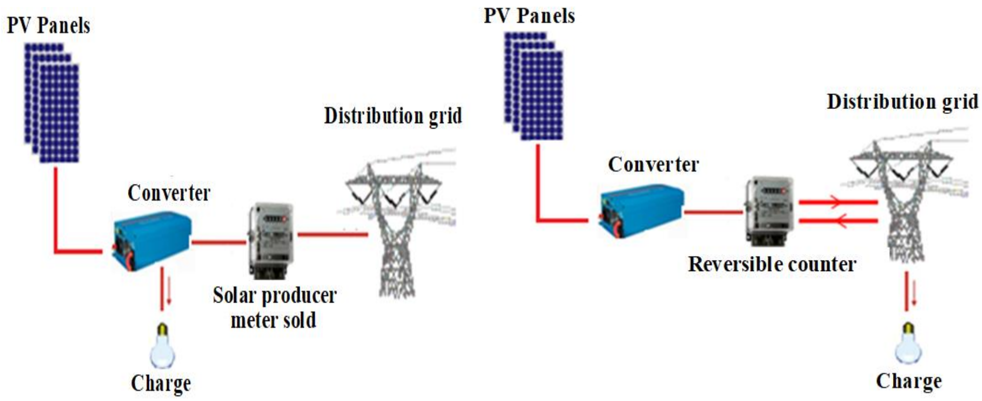


Figure 1.10. Hybrid PV installations [22]

1.14.3. Grid-connected PV systems

A grid-connected PVG does not require energy storage and therefore eliminates the most problematic and expensive link (batteries). In fact, the entire grid serves as an energy reservoir. There are two ways of injecting PV current: either injecting the entire PV production into the grid, or injecting the surplus PV production into the grid.



(a) only its surpluses (b) total production

Figure 1.11.PV installation connected to the grid [22].

1.14.4 Systems operating on the sun (PV pumping)

Generally, photovoltaic pumping systems consist of a PVG, an electric current converter which can be a DC/AC converter for an alternating current motor or a DC/DC converter for a direct current motor and a motor pump unit The PVG is responsible for the instantaneous conversion of solar energy into electrical energy thanks to the photovoltaic effect [23].

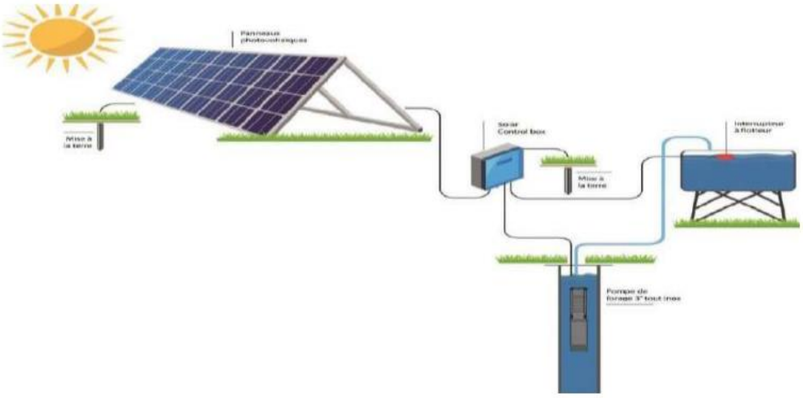


Figure 1.12: Elements of a PV pumping system [24].

1.15. PVG protection system

1.15.1 Bypass diode

The bypass diode is a component used in PV systems to protect solar cells from the negative effects of partial shading or cell failure. When a cell or panel is partially shaded or damaged, the bypass diode allows current to bypass this faulty cell or panel, thus avoiding overheating and the risk of further damage due to the **hot spot** effect. This allows the panel chain to continue operating at peak efficiency, even if one panel experiences a problem.

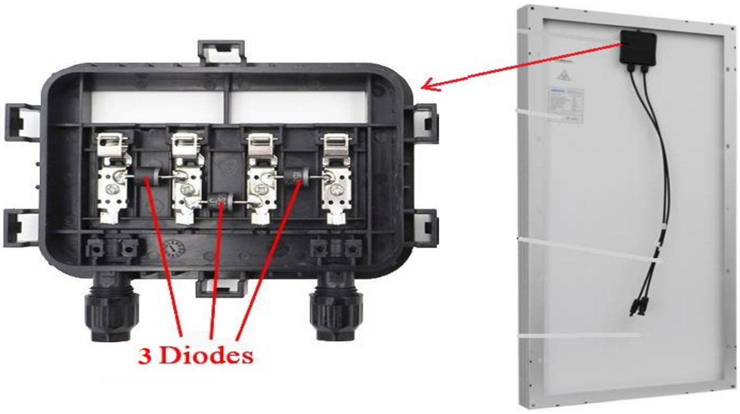


Figure1.13.Bypass diode

1.15.2. Non return diode

A string in a PV array can output a voltage different from that of the others. The string with the lowest voltage output can shade the other strings by absorbing their reverse currents this can lead to reduced efficiency and cause faults related to the flow of reverse current in the string modules. To prevent the flow of current in the reverse path in the string, it is necessary to add diodes. [25] Anti-return devices. Despite their advantages, their presence in the PV system results in a loss of voltage which itself causes a drop in production. On the other hand, these diodes can be the cause of defects and therefore require regular monitoring. Another possible solution is to replace the anti-return diode with a fuse. However, this substitution does not protect the string against the flow of reverse current. Additionally, fuse sizing is required if the string components are to be able to withstand reverse current.

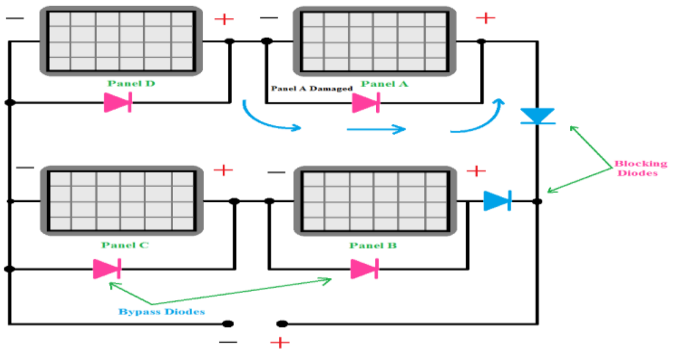


Figure1.14. Anti-return diode

1.16. Advantages and disadvantages of a PV system

Photovoltaic (PV) systems have several advantages and disadvantages that depend on various factors such as location, system scale, and the technologies used. Here is an overview of the main advantages and disadvantages of a photovoltaic system.

1.16.1. Advantages

- **Renewable and clean energy source:** PV systems produce electricity from the sun, a renewable and inexhaustible resource. They do not produce greenhouse gases during operation, thus helping to reduce emissions and dependence on fossil fuels [27].
- **Reduced electricity bills:** Once installed, photovoltaic systems can significantly reduce electricity bills, as the energy generated by the sun is free. In some areas, excess electricity can be sold to the grid [28].
- **Low Maintenance:** Solar panels require little maintenance. Occasional cleaning and regular inspections are generally sufficient. The lifespan of a panel is 25 to 30 years, with a very low failure rate [29].

- **Decentralized energy production:** PV systems enable localized energy production, i.e. generated where it is used, thus reducing losses linked to electricity transmission and improving energy security [30].
- **Flexibility and scalability:** PV systems can be installed on rooftops, integrated into buildings (BIPV), or used in large-scale solar farms. They can also be scaled to different sizes, depending on energy needs [31].
- **Incentives and financial assistance:** Many governments offer grants, tax credits, and financial assistance to encourage the installation of solar panels, making the initial investment more affordable [32].

1.16.2. Disadvantages of PV systems

- **High initial cost:** The cost of purchasing and installing a photovoltaic system can be high, even though solar panel prices have declined in recent years. This includes the cost of the panels, inverters, and installation [33].
- **Intermittency of solar energy:** Photovoltaic systems rely on sunlight, which means they produce less electricity on cloudy days, at night, or in areas with less sunlight. Energy storage solutions or backup systems are needed to ensure a stable power supply, which can increase costs [34].
- **Space requirement:** Generating a significant amount of electricity often requires a large area of panels, which can be a challenge in urban areas or places where space is limited [35].
- **Cost of energy storage**: Energy storage systems (such as batteries) are often needed to make photovoltaic systems more reliable during periods without sunlight. However, these storage solutions are expensive [36].
- **Efficiency Limits**: Commercial solar panel efficiency is typically between 15% and 22%, meaning that much of the sun's energy is not converted into electricity. This inefficiency requires large panel areas to produce enough energy [37].

1.17. Conclusion

In this chapter, we provided a state-of-the-art overview of electricity production and consumption in general and that of renewable sources in the world, as well as the average annual growth rate of renewable sectors, particularly in Algeria. We then presented the Algerian program for the development of renewable energies and energy efficiency (PNEREE).

Chapter 1: State of the art of PV systems

We discussed the principle of photovoltaic solar energy conversion, as well as the different configurations of PV systems, namely: stand-alone PV systems, grid-connected PV systems and finally PV pumping systems. Finally, we presented the advantages and disadvantages of PV systems.

CHAPTER 2: MODELING THE ELEMENTS OF A PV SYSTEM CONNECTED TO THE ELECTRICAL GRID

2.1. Introduction

A grid-connected PV system is a complex system consisting of different interacting elements, each of which acts on the other in different ways within limits imposed by the control strategies employed.

Modeling the various elements of such a system, such as sunlight, PV panels, chopper, inverter, and the electrical grid, requires knowledge of several disciplines: meteorology, electronics, and electrical engineering, and requires a good understanding of the interactions between them. Several simulation codes have been developed for this purpose.

In this chapter, we will present the modeling of a PV system connected to the electrical grid where the mathematical models of the different constituent elements will be developed.

2.2. PV system connected to the electricity grid

The grid-connected PV system under study consists of four parts: a PVG, a DC/DC boost converter to control the maximum power point, a DC/AC converter, and the power grid. The diagram in Figure 1 below represents a typical configuration of the system under study.

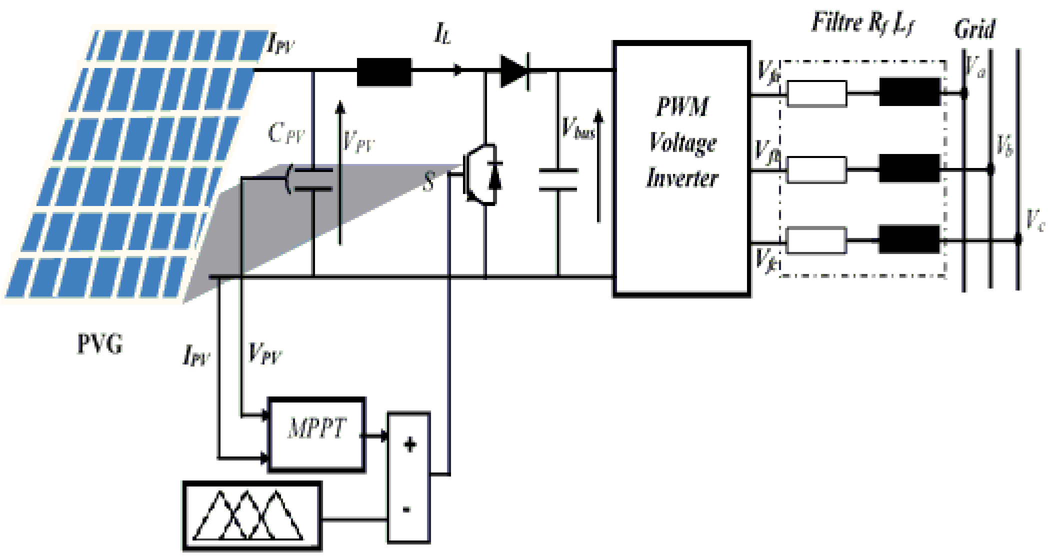


Figure 2.1: Operation of a grid-connected PV power plant

2.2.1. Modeling of the PVG

Combining several PV cells in series gives rise to a PV panel and combining several PV panels in series/parallel gives rise to a PVG. Series/parallel connection makes it possible to obtain the required voltage and current, the performance of which. The behavior of a PV generator can be represented by a characteristic curve of current versus voltage for certain operating conditions, that is, for a given luminous flux and temperature[37].

2.2.1.1 Electrical model

The photovoltaic cell is characterized by its equivalent electrical diagram, consisting of a power source, which models the conversion of the luminous flux into electrical energy, a shunt resistance R_{sh} which represents the leakage currents in the PN junction, a series resistor R_s, which represents contact and connection losses, and a diode connected in parallel, which models the PN junction.

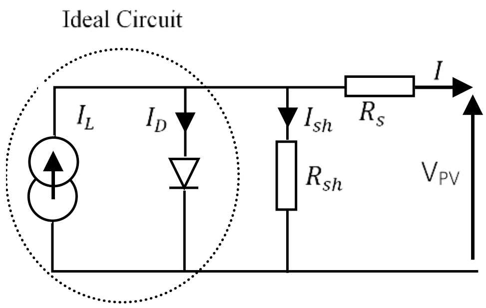


Figure 2.2. Equivalent diagram of a PV cell (module) Single diode model

The modeling is represented by the following equation:

$$I = I_L - I_d - I_{sh} \tag{2.1}$$

Or:

I_L : Cell photocurrent proportional to the illumination φ. This current also corresponds to the short-circuit current Isc. as written in (1.2):

$$I_L = \left(\frac{G}{G_{ref}}\right).\left(I_{L,ref} + \mu_{Isc}.(T_C - T_{C,ref})\right) \tag{2.2}$$

Or:

G, G_{ref}: the actual and reference lighting conditions (W/m²).

μ_{Isc}: the temperature coefficient of the short-circuit current (A/°K).

Tc, Tcref: the actual and reference temperature conditions (°K).

I_D: is the diode current, and can be expressed as follows:

$$I_D = I_0\left(e^{\frac{q(V+R_S I)}{nkT}} - 1\right) \tag{2.3}$$

With:

$$I_0 = I_{0ref}\cdot\left(\frac{T_c}{T_{Cref}}\right)^3\left[\left(e^{\frac{E_g}{V_T}}\right).\left(\frac{1}{T_{Cref}} - \frac{1}{T_C}\right)\right] \tag{2.4}$$

and:

$$I_{0ref} = \frac{I_{sc,ref}}{\exp\left(\frac{qV_{oc\_ref}}{AKT_C}\right)-1} \tag{2.5}$$

Thus, equation (2.1) can be written in more detail after substituting (2.2) and (2.3):

$$I = I_L - \left[I_0\left(e^{\frac{V_{PV}+IR_S}{V_T}}\right) - 1\right] - \frac{V_{PV}+IR_S}{R_{sh}} \tag{2.6}$$

- The thermodynamic potential $V_T = \frac{nkT}{q}$
- I_0 : reverse saturation current of the diode.
- q : electron charge ($1.6*10^{-19}$C).
- k : Boltzmann constant ($1.38*10^{-23}$ j/k)
- Eg : band gap energy of the material (1.12 eV for silicon).
- n : ideality factor of the solar cell, between 1 and 5 in practice.
- T : junction temperature in K[38].

2.2.1.2 External Parameters

These parameters can be determined from the I(V) curves, or from equation (2.2).The following are the most common [39]:

- **Short-circuit current:** Current delivered by a short-circuited cell for "full sunlight", i.e. when the (+) pole is connected to the (−) pole, the voltage at its terminals is then zero (see figure2.2). In this case, the power supplied by the cell P = V × I is zero. Its expression is expressed as:

$$\mathrm{I_{sc}} = \mathrm{I_{ph}} - \mathrm{I_0}\left(\mathrm{e}^{\frac{(\mathrm{R_S I_{sc}})}{\mathrm{V_T}}} - 1\right) - \frac{\mathrm{R_S I_{sc}}}{\mathrm{R_{sh}}} \tag{2.7}$$

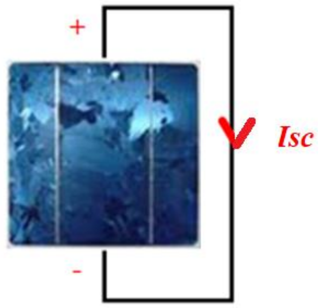


Figure 2.3.Short-circuit current

- **The open circuit voltage V_{oc}**

Voltage at the cell terminals in the absence of any current, for "full sunlight", i.e. when the (+) pole and the (−) pole are electrically isolated from any other electrical circuit (figure 2.4) the current passing through it is then zero. In this case, the power provided by the cell P = V × I is zero.Its expression is expressed as:

$$0 = I_{PV} - I_0\left(e^{\frac{V_{oc}}{V_T}} - 1\right) - \frac{V_{oc}}{R_{sh}} \qquad (2.8)$$

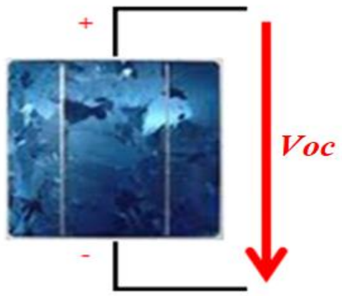


Figure 2.4. Open circuit voltage

In the ideal case, its value is slightly less than:

$$V_{oc} = V_T \ln\left(\frac{I_{ph}}{I_0} + 1\right) \qquad (2.9)$$

- **The form factor (FF)** : is defined as the ratio between the maximum power that can deliver the cell noted Pmpp and the power formed by the product ($I_{sc} \times V_{oc}$), it is defined by:

$$FF = \left(\frac{V_M I_M}{V_{co} I_{cc}}\right) \qquad (2.10)$$

This factor shows the deviation of the I(V) curve from a rectangle (of V_{CO} length and I_{SC} width), which corresponds to the ideal solar cell.

The power of PV modules is expressed in Watt-peak. The latter represents the power provided by a module when it is closed on its nominal (optimal) load, under an illumination of 1000 W/m² and at a temperature of 25°C.

- **Efficiency:** The power is zero in short circuit and in open circuit. It passes through a maximum when the characteristic I (V) is traversed. The ratio of optimum electrical power to forward power.

$$\eta = P_M / P_0 \tag{2.11}$$

P_0: is the incident power. It is equal to the product of the illumination and the total surface of the solar cells $P_0 = G*S$.

- G: Overall flux [W/m²].
- S: PV Generator area [m²].

2.2.1.3. Association of solar cells, PV module [39]

The power available at the terminals of a cell is very low (about 3 W). To increase this power, these cells are assembled either in series (to increase the voltage) or in parallel (to increase the current). These cells are protected from humidity by encapsulation in an EVA polymer (ethylene vinyl-acetate) and protected on the front surface of a glass, tempered with high transmission and on the back surface of a sheet of Tedlar (Polyvinyl fluoride). The cells are assembled to form an elementary PVG (PV module) which is usually surrounded by a rigid anodized aluminum frame including fixing holes.

The typical PV module cells are separated into several segments which are protected by anti-parallel diodes. If one of these cells were to be shaded, the diode would trigger in order to protect the cells of this part of the module.

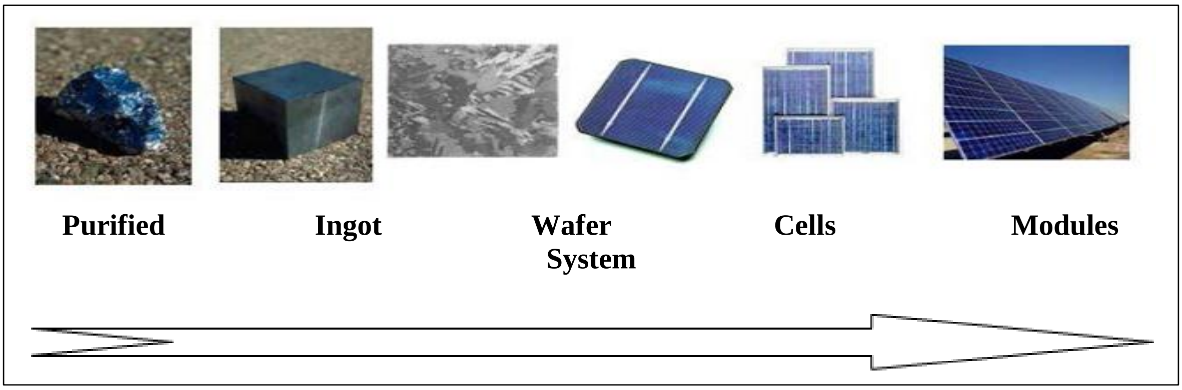


Figure 2.5: Evolution of constructions of PV production systems

In order to obtain powers from a few kW to a few MW, under a suitable voltage, it is necessary to mount the modules in series-parallel rows to form what is called a PV field.

- **Serial Association**

When Ns PV cells are associated in series, the voltages of these cells add up and the current generated is the same throughout the branch (Fig.2.6).

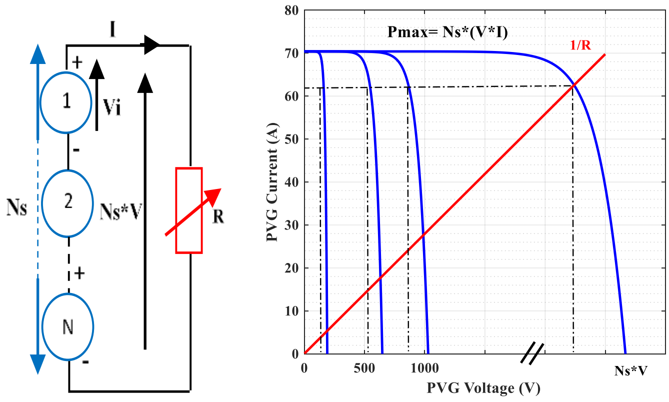


Fig.2.6. Series Cells.

Parallel Connection

Connecting multiple cells in parallel increases the current for the same voltage.

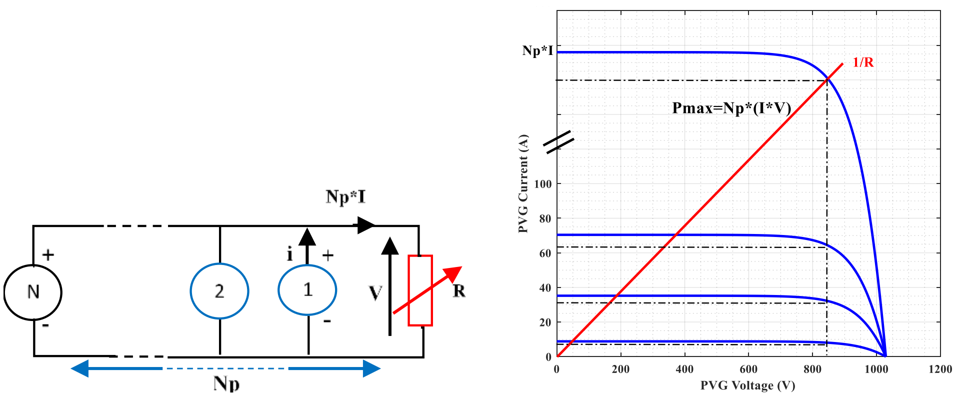


Fig.2.7. Parallel cells

Series/parallel association

If you want a precise voltage and current, opt for the mixed connection. It is a type of connection both in series and in parallel.

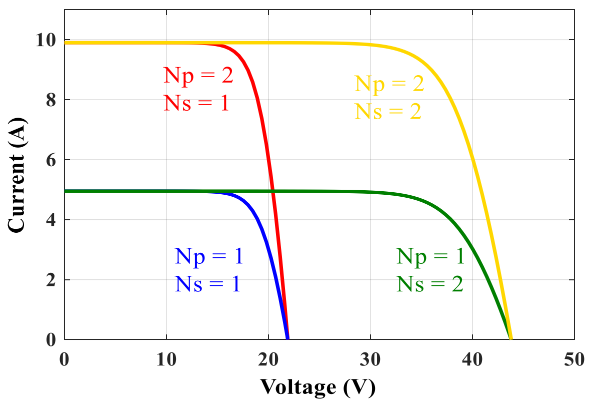


Figure.2.8. Series/parallel association connection

The equation relating to a mixed group formed by placing β cells in series and α in parallel is as follows:

$$I = \alpha I_{cc}\left(\frac{\varphi}{1000}\right) - \alpha I_0\left(e^{\frac{\left(\beta V+\frac{\beta R_S}{\alpha}I\right)}{\beta V_T}}\right) - \frac{\beta V+\frac{\beta R_S}{\alpha}I}{\frac{\beta}{\alpha}R_{sh}} \tag{2.12}$$

2.2.1.4. I (V) and P (V) characteristics of a PVG under STC conditions [41]

Standard test conditions define how PV modules are examined in the laboratory in order to identify their electrical properties. It is standardized conditions that allow modules to be compared with each other. The STC conditions give a number of test conditions including:

1°) Module illumination level: G = 1000 W/m²

2°) Cell temperature: 25 °C

3°) Air mass coefficient = 1.5.

The peak power of a module is defined as the maximum power of the module in the STC conditions. We will take an example for a module composed of **72 cells** in series presents the following electrical properties (under STC conditions):

- Short-circuit current I_{sc} = 6.05 A
- Open circuit voltage V_{oc} = 0.67 × 72 = 48.2 V
- Maximum power current I_{mpp} = 5.68 A
- Maximum power voltage V_{mpp} = 0.57 × 72 = 40.5 V
- Maximum power module P_{mpp} = 7.57 × 26.4 = 230 W

- Maximum power $PVGP_M$ = 53 kWc

The IV and PV characteristic of this module is given below in figures 2.9 and 2.10:

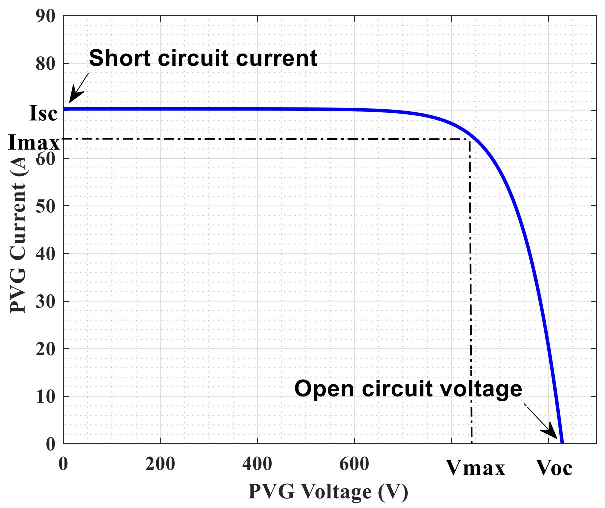


Fig 2.9.Current/voltage characteristics

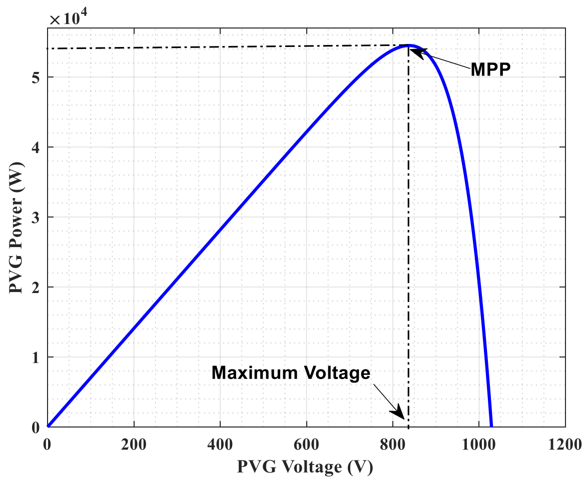


Fig.2.10. Power/voltage characteristics

2.2.1.5. Influence of weather conditions on the characteristics of a PVG

- Influence of solar radiation

We maintained a constant temperature of 25°C and different illuminations (Fig 2.11).The increase in short-circuit current is much greater than the increase in open-circuit voltage, because the short-circuit current (I_{SC}) is a linear function of the illumination and the open-circuit voltage (V_{OC}) is a logarithmic function.

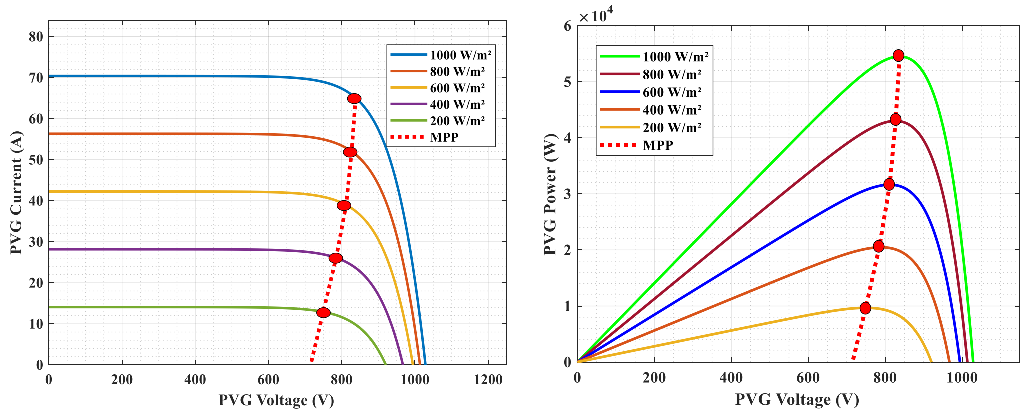


Figure.2.11. Influence of illumination on the I(V) and P(V) characteristics

- Influence of temperature

We performed a simulation where we maintained a constant illumination of 1000 W/m² for different temperatures (Fig.2.12). The characteristic curve will present different shapes depending on the temperature. The open-circuit voltage will decrease with the temperature, the opposite of the short-circuit current. The variation in open-circuit voltage is practically compensated by the variation in short-circuit current, and the nominal power supplied by a cell will therefore vary very slightly with the junction temperature [42].

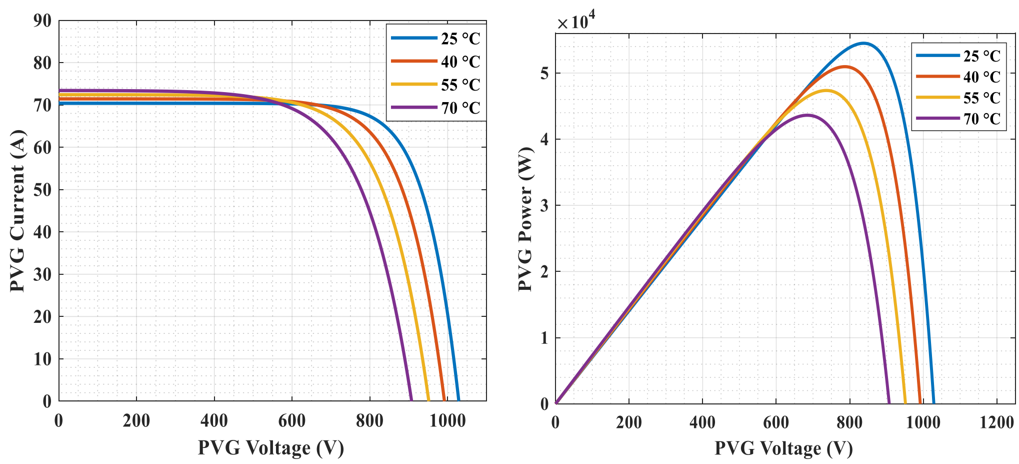


Figure .2.12. Influence of temperature on the I(V) and P(V) characteristics

2.2.1.6. PV module protection system

- Influence of shading on the characteristics of a PVG

The output power of the module is equal to the total output power of all PV cells under uniform solar irradiance. But under non-uniform irradiance condition, e.g. shadow (shadow from trees, neighbor's house or from one PV panel to another), as shown in

Figure (2.13),some of these photocells will behave as a receiver, in direct or reverse polarization causing an increase in the temperature of these photocells and can damage the PV module.

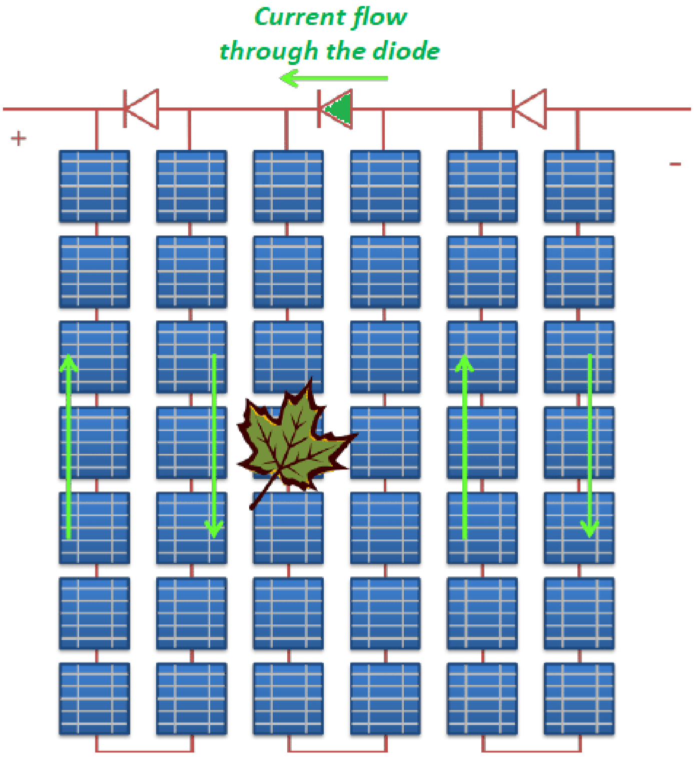


Fig.2.13. Operation of a PVG under partial shading

Electrical protections must be integrated into PV modules to avoid damaging failures related to the connection of cells in series and panels in parallel, thus ensuring a long service life. In current installations, two forms of conventional protection are used for this purpose figure (2.13).

Bypass diode: The bypass diode is connected in antiparallel with a group of cells to protect the weakest cell against reverse bias (Figure 2.14). The maximum power of a PV cell decreases when shaded, and the PV characteristics have many local maximum power points (MPPs), making tracking the overall MPP difficult (Figure 2.15).Most PV modules consist of sub-arrays of cells connected in series with a bypass diode to avoid these problems (Figures 2.15 and 2.16). In the event of partial failure, the number of cells per sub-array as well as the number of bypass diodes represent an economic compromise between protection and the loss of a significant part of the PVG, and are generally limited to 5 (Figure 2.15)[43][44].

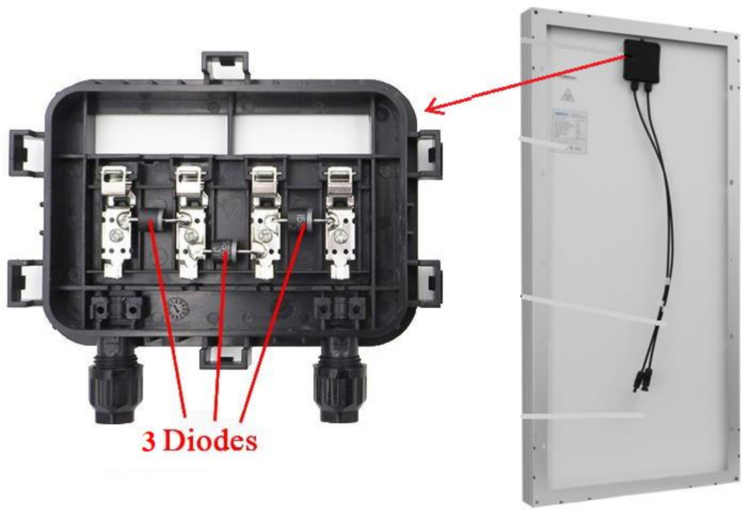


Figure 2.14:Position of the bypass diode

• **Anti-reverse diode:** Blocking (anti-reverse) diodes prevent the reversal of current flow between strings of modules connected in parallel (Figure 2.14). This phenomenon can occur when many modules are connected in parallel or when a directly connected load, such as a battery, can switch from sink mode to generator mode during the night**.**

The I(V) and P(V) curves in normal operation and under shading are shown in figure (2.15).

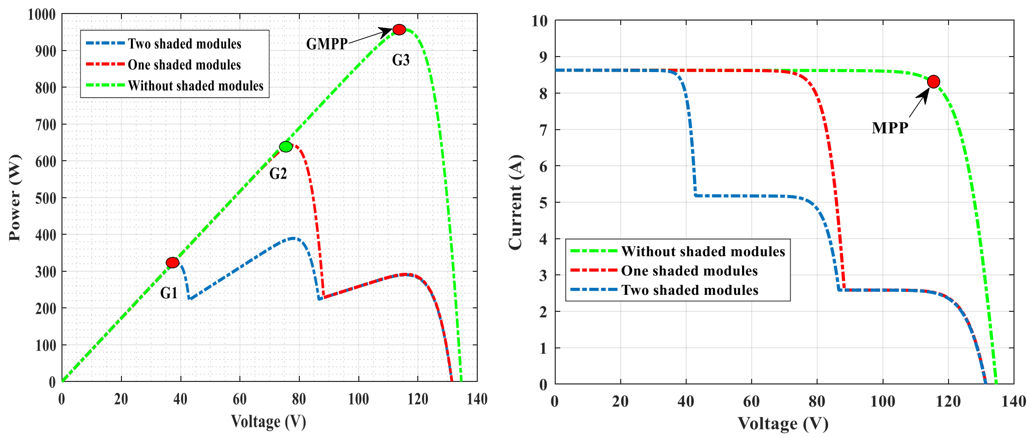


Fig.2.15. I(V) and P(V) characteristics in normal operation and under shading

2.2.2. Modeling of the DC-DC converter (CHOPPER) BOOST

In power electronic converters, choppers are static energy devices that transmit electrical energy from one DC source to another DC source [45][46]. They are defined by their duty cycle D. A distinction is made between boost choppers, buck choppers and buck-boost choppers.

The boost converter converts a DC voltage into another DC voltage of higher value and the same polarity. Figure 2.16 shows the schematic of the boost converter. It consists of a power switch S (MOSFET transistor), an amplification inductor L, the filter capacitor C and the output diode D.

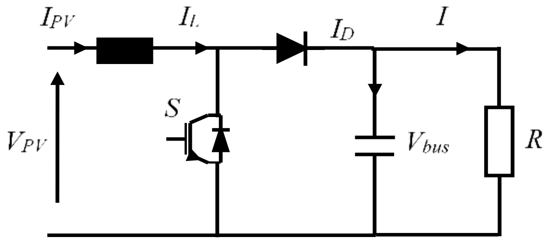


Figure 2.16.shows the schematic of the boost converter.

The boost converter is inserted between the PVG and the DC/AC converter. The dynamic model can be expressed by the following equations:

$$\begin{cases} L\frac{di_L}{dt} = -(1-D).V_{bus} + V_{PV} \\ C_{bus}\frac{dV_{bus}}{dt} = (1-D)i_L - \frac{V_{bus}}{R} \\ C_{PV}\frac{dV_{PV}}{dt} = i_{PV} - i_L \end{cases} \quad (2.13)$$

When switch S is turned on, the current in the boost inductor increases linearly, and at this point, the diode is turned off. When switch S is turned off, the energy stored in the inductor is released through the diode to the output circuit. The pulsating current produced by switching is smoothed by the capacitive filter, and a DC voltage is supplied to the load [47][48].

2.2.3. Optimal operation of the PVG

The electrical power produced by a PVG depends heavily on sunlight and, to a lesser extent, on temperature, but also on the overall aging of the system. For these reasons, the PVG can only provide maximum power for a specific voltage and a specific current.

This maximum power operation depends on the load at its terminals. In order to extract the maximum power available at the PVG terminals at any time and transfer it to the load, an adaptation stage must be integrated between the PVG and the load. The latter must be capable of operating the PVG at its maximum power.In order to achieve this objective, the adaptation stage must be equipped with an MPPT control, which will act on its duty cycle according to variations in weather conditions or the load that may occur [49].

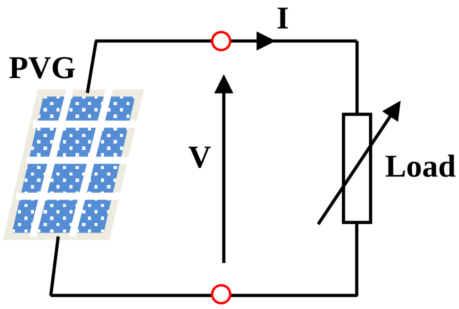


Figure 2.17. Direct PVG – charging connection

For the PVG to operate in optimal mode, the commonly adopted solution is to insert a boost chopper, which acts as a source-load adapter [50].

2.2.3.1. A synthesis of the different MPPTs found in the literature

MPPT (Maximum Power Point Tracking) control is an essential control for optimal operation of the photovoltaic system. Its principle is based on the automatic variation of the duty cycle (α) of the DC/DC converter in order to maximize the power delivered by the PVG by bringing it to the optimal value [51][52].

There are several MPPT control algorithms (analog or digital):

- Fixed Duty Cycle (constant duty cycle);
- Constant Voltage (constant voltage);
- Incremental Conductance;
- Constant Current algorithm;
- Constant Voltage algorithm;
- Perturb and Observe (P&O);
- Algorithm based on fuzzy logic

2.2.3.2. MPPT operating principle

The tracking method known as MPPT (Maximum Power Point Tracking) is a control system that allows a non-linear electrical generator to operate in such a way as to constantly produce its maximum power. MPPT systems are usually associated with PVG or even with wind generators. The MPPT method is based on the use of a search algorithm where the maximum of the power curve is estimated without interrupting the normal operation of the PVG.

An MPPT controller then allows the static converter connecting the load and the PVG to be controlled in such a way as to continuously provide the maximum power. Figure

(2.18) represents the trajectory of the maximum power point produced by the PVG. Note that tracking plays a very important role because it maximizes efficiency and reduces cost[53][54].

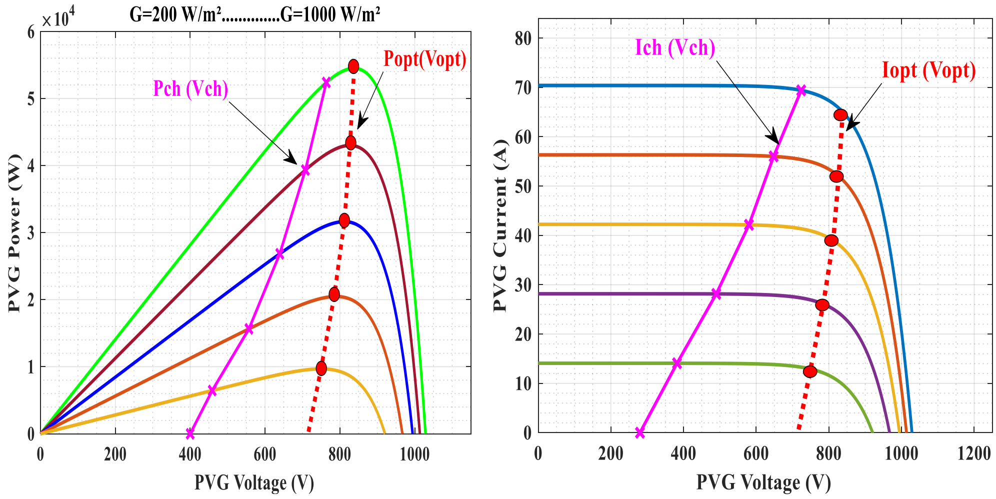


Figure 2.18. Charging voltages and powers for direct coupling and with MPPT

When a PVG is directly coupled to a load, the operating point of the PVG under constant irradiation is the intersection of its current–voltage characteristic curve I=f (V) with the load line Ich=f(V), this operating point is not necessarily the maximum power point (MPP). So in direct coupling, PVG are often oversized to ensure sufficient power to be supplied to the load during low irradiation months; this leads to an excessively expensive system.

Despite the advantages of direct coupling, it remains that this type of coupling is only possible under specific conditions (temperature, illumination, type and parameters of the load). Therefore, more sophisticated techniques must be used.

2.2.3.3. Perturb-and-Observe (P&O) Method

The "Perturb-and-Observe" (P&O) algorithm is well known and continues to be the most widely used method in MPPT modules because it is simple and requires only voltage and current measurements of the PV and PV modules, respectively. As its name suggests the P&O method works by perturbing the PV voltage and observing the impact of this change on the PV output power.

The PVG is considered to operate at a point that is not necessarily the MPP. The operating voltage is disturbed with (dV) and the variation (dP) in electrical power is observed. If (dP) is positive, then the voltage disturbance moves the operating point to a point closer to the MPP.

Further successive voltage disturbances in the same direction (i.e., with the same algebraic sign) should move the operating point until the MPP is reached. In the case where (dP) is negative, the operating point moves away from the MPP, and therefore the algebraic sign of the voltage disturbance should be reversed to move the operating point back towards the MPP.

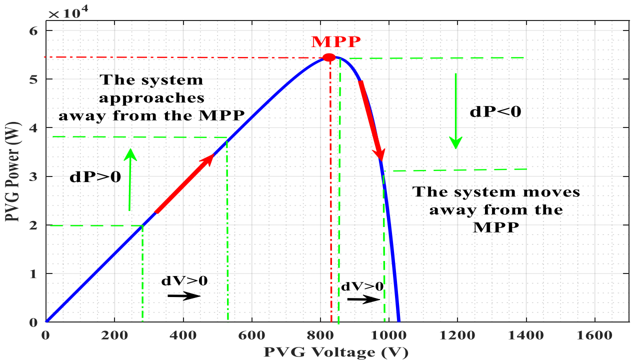


Figure 2.19. Sign of dP/dV at different positions of the characteristic curve of P_{PV} and V_{PV}[55]

Figure 2.20 shows the flowchart of the algorithm of the ‘P&O’ method as it is to be implemented in a control microprocessor [56]:

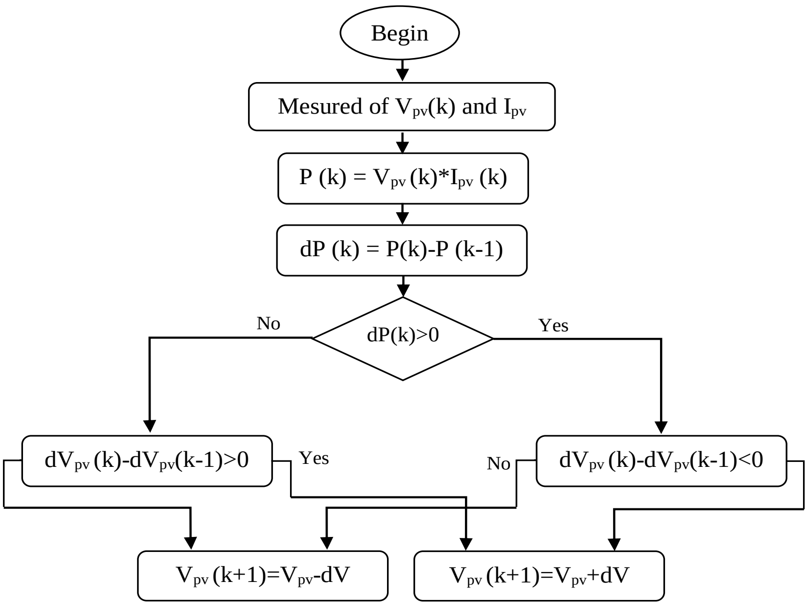


Figure 2.20. Flowchart of the P&O method

2.3 Quality and standards of grid-connected PV systems

The quality and standards of a grid-connected system include the following aspects:

- Decoupling of PV systems from the grid in the event of a grid failure to avoid islanding problems**;**
- Maintaining the quality of the energy supplied to the grid by minimizing harmonic pollution
- Avoiding multiple effects on a portion of the grid, such as single-phase and three-phase imbalances;
- Ensuring grid stability by mitigating frequency fluctuations and voltage drops.

These measures are essential to ensure reliable and efficient integration of PV systems into the grid, thus minimizing any potential negative impact on grid stability and power quality. Compliance with these standards helps maintain stable and harmonious operation between solar power generation and the electricity grid.

2.4. Conclusion

In this chapter, we presented the principle of conversion and modeling of a PV system, the characteristics and its performance. We also saw in this chapter the analysis of the static DC/DC boost converter used as an interface between the load and the PVG so that it operates at optimal efficiency in addition to the classic MPPT control (P&O method) for finding the point where the power of the PVG is maximum.

CHAPTER 3: INFLUENCES OF THE GRID ON THE INVERTER AND OF THE INVERTER ON THE GRID

3.1. Introduction

The penetration of renewable energy (especially solar energy) into the electricity grid has increased in recent years. Grid-connected PV systems are always connected to the electricity grid via a suitable inverter, as a PV module only provides direct current. Figure 3.1 illustrates the configuration of a grid-connected PV system. The PV array is connected to the DC bus via a DC/DC boost converter and then to the AC grid via a DC/AC inverter. The inverter has its own control purpose (the boost inverter controls the PV array to generate maximum power, while the grid inverter controls the active and reactive currents of the AC bus to be constant).

An inverter is a static converter that converts electrical energy from DC to AC. In fact, this energy conversion is achieved by means of a control device (semiconductors). It allows to obtain at the terminals of the receiver an alternating voltage adjustable in frequency and effective value, thus using an appropriate control sequence [57].

3.2. Operating principle of the DC-AC converter (INVERTER)

An inverter is an electronic device that provides static conversion of direct voltage or current into alternating voltage or current. It is said to be autonomous if it ensures its own frequency and waveform.The functions of the inverter are to convert and transmit the electricity produced with maximum efficiency and in complete safety to the electricity grid in the case of grid-connected sites or to the user in the case of isolated sites.

Two types of inverters are therefore used to ensure such a conversion [58]:

- Single-phase inverter
- Three-phase inverter.

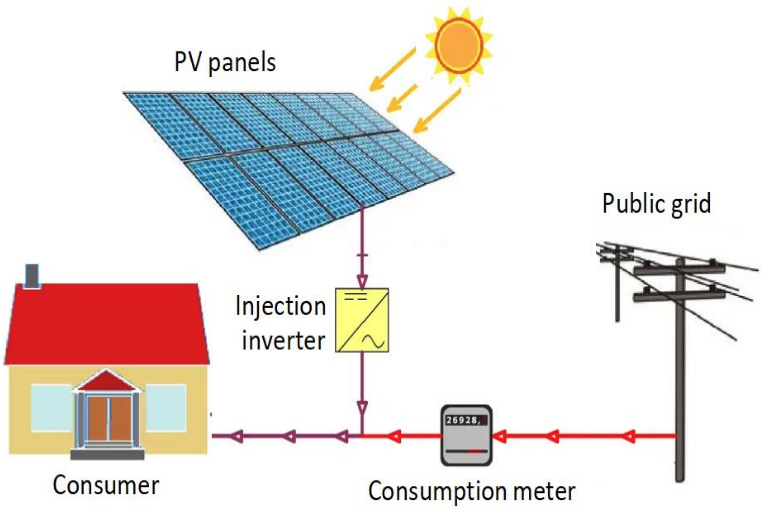


Figure 3.1: Principle of a grid-connected PV system

3.2.1 Single-phase inverter

This device allows the transmission of power from a production source to the single-phase electrical grid (grid with neutral distribution). In order to generate (and send) an alternating current to the electrical grid, the voltage of the direct bus (Vdc) must be higher than the peak value of the voltage appearing on the filter side.

For this converter, an idealized switch is synthesized by placing an IGBT and a diode in anti-parallel [59].

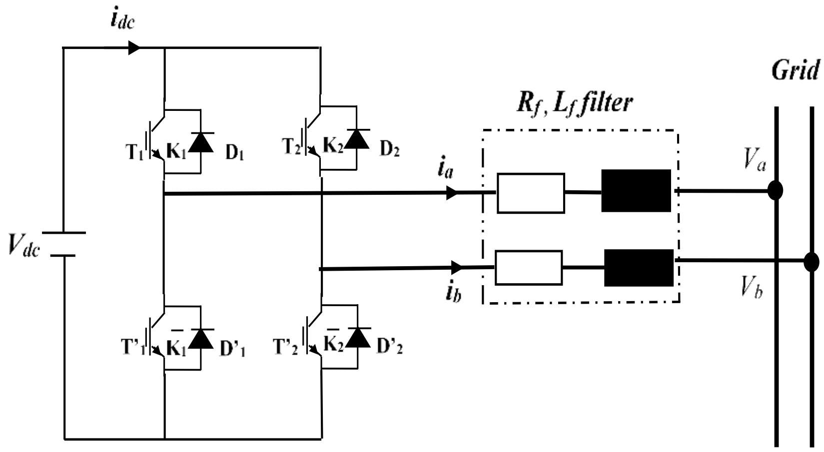


Figure.3.2: Single-phase voltage inverter

3.2.2 Three-phase inverter

The role of the three-phase inverter is the same as its single-phase equivalent. It involves transferring power from the source to the grid. It is necessary to establish a constant voltage across the capacitor terminals. And, unlike the single-phase application, to create a system of balanced three-phase currents sent to the grid.

After rectification, it allows voltage waves of varying amplitudes and frequencies to be applied to the grid from a direct voltage.

The converter considered in our study is the one connected to the grid via a filter (Rf, Lf) [60].

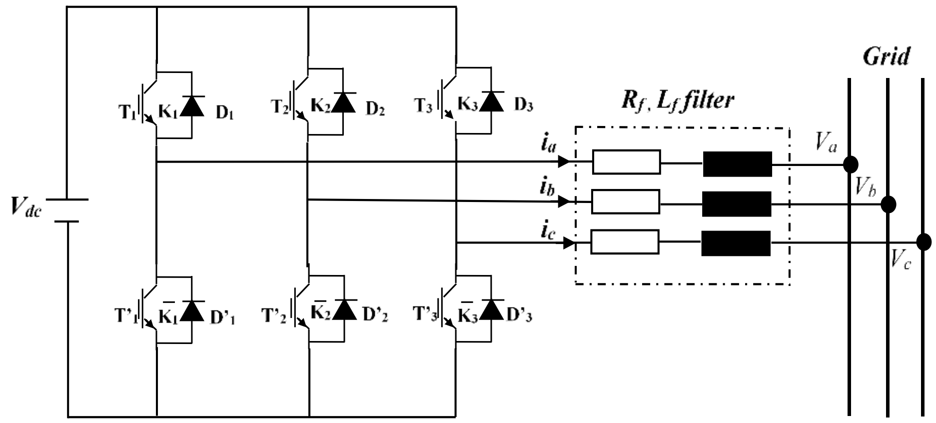


Figure.3.3: Diagram of a three-phase inverter

3.3. Selection criteria and architectures of inverters connected to the electrical grid

Inverters are no longer limited to transforming the direct current (DC) power generated by solar panels into alternating current in the form of a sinusoidal voltage of the desired frequency (e.g. 230V/400V - 50Hz) but also exploit the power delivered by the PVG by forcing it to operate at its maximum power point.

In addition, they provide reliable grid monitoring to protect the grid from outages and interrupt power supply in the event of problems arising from either the grid or the installation.

Among the criteria for selecting an inverter, we cite:

- **Power:** Power is the primary criterion for choosing an inverter. Indeed, an inverter must have sufficient power to feed into the grid. It is expressed in Volt-Amps (VA).
- **Type of electrical fault:** When choosing an inverter, you must also consider the type of problem that will need to be resolved.

- **Type of use:** The type of use is also an important criterion, if not the most important, when choosing an inverter. Each type of inverter is suitable for a specific category of activity (stand-alone, grid-connected, or PV pumping).

Currently, there are mainly three inverter architectures that provide good technical solutions:Central inverter, string inverters and panel-integrated inverters. We briefly describe their properties below [61].

3.3.1. Central inverter

The device shown in figure (3.4) is the simplest, as it has the fewest components possible. Several PV modules are connected in series to obtain a sufficiently high DC voltage. The DC voltage obtained directly feeds a central inverter, which provides the desired sinusoidal voltage (380 V).The central inverter has at least one MPPT control system that allows it to operate at its PPM. This works perfectly as long as the panels are identical and operate under uniform sunlight. But when the electrical characteristics between the panels differ due to shading, soiling, aging or stress, the MPPT control becomes uncertain and the PV array does not produce as much as it could [62].

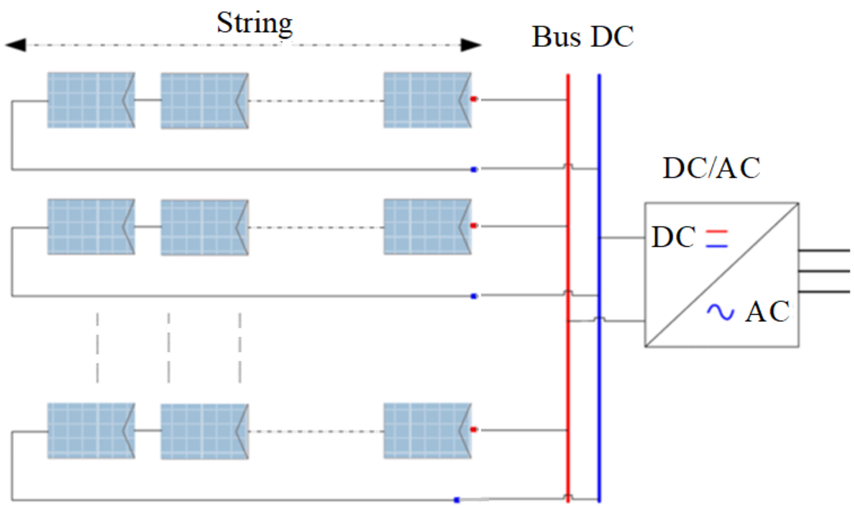


Figure 3.4: Principle diagrams of a central inverter

The major drawback of this device is the total and immediate shutdown of energy production when a problem occurs upstream of the inverter.

3.3.2. Branch inverters

As with the central inverter, the PV field is also made up of strings. Each string can therefore operate at its own PPM. Each string is equipped with an inverter, which can also be equipped with an MPPT type control system (Fig 3.5).

This technology significantly reduces the risk of adaptation problems and losses due to shading effects, while eliminating those caused by non-return diodes. These advantageous technical properties increase the reliability of the installation as well as its production. Energy. However, the high number of inverters will generate an additional cost compared to the previous topology [63].

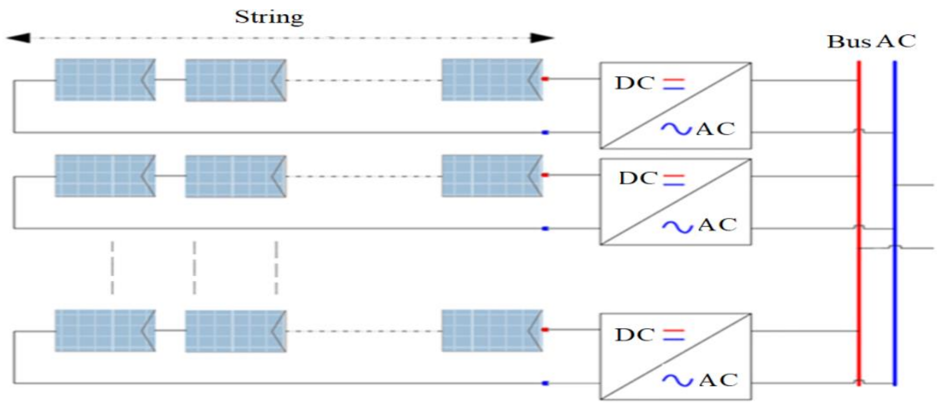


Figure3.5: String inverter principle diagrams

However, one parameter still remains uncertain in MPPT control when the string power characteristic has multiple power peaks. In this case, the inverter may operate at a false maximum power point and therefore, the delivered power will not be the maximum available power. This configuration can occur in different configurations as shown in (Fig.3.6).

Figure 3.6: Examples of PV installations requiring multiple inverters.

Some of the panels may be dirty or hidden by shadows or snow, or the orientation of the panels in the same string may not be identical for all panels. A non-optimal arrangement of the panels therefore means that a string may receive in homogeneous irradiance that can disrupt the search for the PPM. The solution in terms of energy gain is to move towards more individual management of the panels by integrating, for example, an adaptation stage by PVG.

3.3.3. Modular inverters

For this type of topology, each photovoltaic panel has its own inverter, which avoids the constraints associated with imbalance problems between the different PV panels. However, the very high number of inverters and the cabling of the installation generates additional costs.

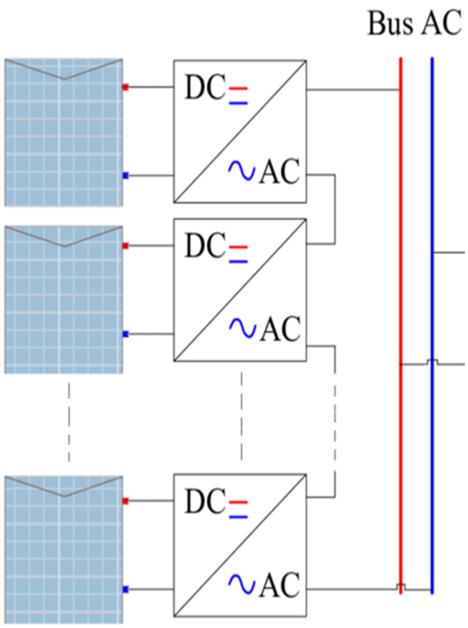


Figure 3.7: Integrated inverter

Table 3.1: Technical characteristics of the different configuration systems

Inverter Type	**Central**	**String**	**Modular**
PV voltage	340-800 V	150-800 V	17-90 V
DC losses (Ω)	≈ 1-5% depending on voltage and distance	≈ 1% depending on voltage and distance	Negligible
η_{conv}	95-97%	92-96%	87-93%
Maintenance and repair	Simple	Difficult (search for malfunction)	Difficult (search for malfunction)

3.4. Modeling of the inverter

We are interested in modeling the power converter in the three-phase frame, then in the two-phase Park frame. The Pulse Width Modulated (PWM) voltage inverter is a static DC-AC converter consisting of switching cells generally with IGBT transistors or GTO thyristors for high powers.

After rectification, it allows voltage waves with variable amplitudes and frequencies to be imposed on either the machine or the grid from a direct voltage [64].The converter considered in our study is the one connected either to the grid via a filter (Rf, Lf),

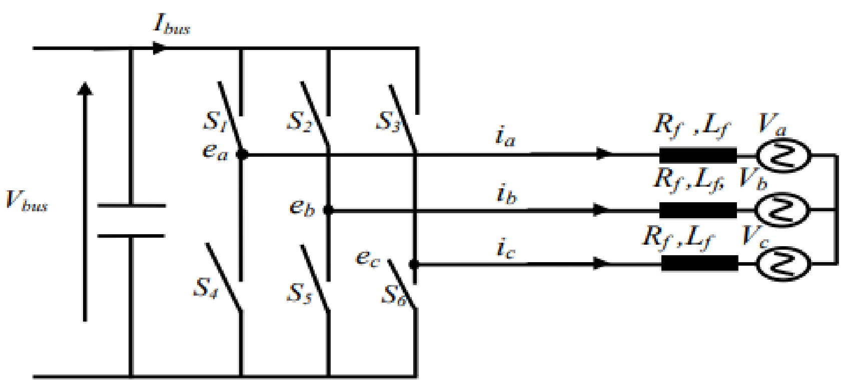


Figure 3.8: Diagram of a three-phase PWM inverter.

The switches (S1, S2, S3, S4, S5, S6) must be controlled in a complementary manner to ensure the continuity of the alternating currents in the load on the one hand and to avoid short-circuiting the source on the other hand.

3.4.1. Inverter model and pulse width modulation (PWM)

The basic principle of pulse width modulation is based on the cutting of a full rectangular wave. Thus, the output voltage of the inverter is formed by a series of square waves of amplitude equal to the supply voltage (continuous) and of variable width. The most widespread technique for reproducing a PWM signal is to compare a triangular signal called a high-frequency carrier to a reference signal called a modulator, which constitutes the energy of the signal collected at the output of the inverter.

The vector of simple voltages at the output of the inverter is written in matrix form as follows:

$$\begin{bmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{bmatrix} = \frac{V_{bus}}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{3.1}$$

If i_a, i_b, i_c are the currents in the alternating part, the current in the direct part can be obtained from the law of conservation of power. Using the expression for it:

$$V_{bus} \cdot I_{bus} = V_{C1} I_{r1} + V_{C2} I_{r2} + V_{C3} I_{r3} \tag{3.2}$$

$$I_{bus} = f_1(S_1, S_4) \cdot i_a + f_2(S_2, S_5) \cdot i_b + f_3(S_3, S_6) \cdot i_c \tag{3.3}$$

The figures (3.9 and 3.10) represent the carrier signal, the reference signals, and the voltage of one phase at the output of the inverter.

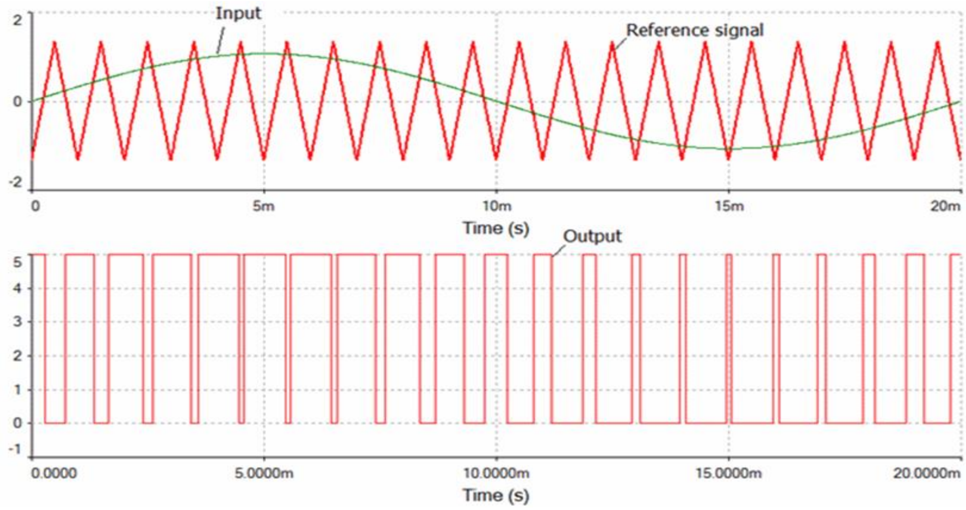


Figure. 3.9. Diagram delivered by a PWM command

The modulation index of a three-phase inverter refers to a key parameter that characterizes the relationship between the control signal (often sinusoidal) and the carrier signal (often triangle or sawtooth shaped) in a technique called pulse width modulation (PWM). The modulation index ma is used to control the inverter output voltage. There are two types of modulation indices:

3.4.1.1. Amplitude modulation index ma (or voltage modulation)

This is the most common. It is defined as:

$$m_a = \frac{V_{ref}}{V_{carrier}} \tag{3.4}$$

With: V_{ref} is the amplitude of the reference sinusoid (the signal to be generated) and $V_{carrier}$ is the triangular carrier signal amplitude.

- m_a<1, we are in **linear modulation** (good operation);
- m_a>1, we are in **over-modulation**, which leads to distortions and a loss of linearity;
- Theoretical max $m_a \approx 1.15$ (for pure sine PWM).

3.4.1.2. Frequency modulation index m_f

$$m_f = \frac{f_{carrier}}{f_{ref}} \tag{3.5}$$

With:

$f_{carrier}$ is the frequency of the triangular signal and f_{ref} is the reference signal frequency.

A high index m_f>1 allows better waveform resolution but increases switching losses.

3.5. Continuous bus control

The voltage regulation of the DC link (V_{bus}) is designed to maintain a constant reference value situated between DC-DC boost converter and inverter by controlling the process of charge and discharge of the capacitor [65][66]. The current in the branch of the capacitor is given by:

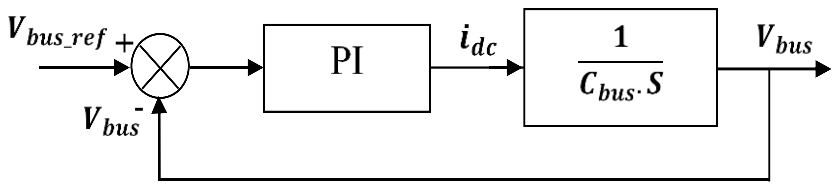


Figure 3.10. Control loop of the DC bus voltage

$$i_{dc} = C_{bus}.\frac{dV_{bus}}{dt} = i_L - i_{inv} \tag{3.6}$$

In the Laplace domain, the above equation can be rewritten as follows:

$$V_{bus} = \frac{i_{dc}}{C_{bus}\ .S} \quad (3.7)$$

The PI controller parameters are deduced by comparing the closed-loop transfer function with the transfer function of the second-order system as follows:

$$\frac{V_{bus\_ref}}{V_{bus}} = \frac{\frac{K_P.S+K_i}{C}}{S^2+\frac{K_P}{C}.S+\frac{K_i}{C}} = \frac{\omega^2{}_n}{S^2+2\xi\omega_n.S+\omega^2{}_n} \quad (3.8)$$

From Equation (9), the controller parameters are:

$$\begin{cases} K_i = C.\omega^2{}_n \\ K_P = 2\xi.\omega_n.C \end{cases} \quad (3.9)$$

3.6 The harmonic distortion rate

Total harmonic distortion (THD) is an indicator of the quality of signal processing in a device. THD is a measure of the linearity of signal processing performed by comparing the output signal of a device to a perfectly sinusoidal input signal. The non-linearity of the system distorts this sinusoid. It is defined by the ratio of the effective value of the signal to the fundamental component.

- **Representation of harmonics:**

The harmonics are represented by a frequency spectrum. The output voltage can be represented by a Fourier series:

$$U(t) = \sum_{k\geq 1}\left(\frac{4E}{k\pi}.\cos\frac{k\beta}{2}\right).\sin(kwt) \quad (3.10)$$

Where: k is odd (impair)

This Fourier series represents the harmonics during k.

$\sin(kwt)$: Harmonics;

$\frac{4E}{k\pi}.\cos\frac{k\beta}{2}$: Amplitude.

3.7. PLL phase-locked Loop

By definition, a PLL is a non-linear feedback control system that is implemented in the synchronous reference frame and synchronizes its output signal with the fundamental component of the grid voltage, which is its input signal. Regardless of the application used, three parts are found in almost all PLLs. These elements are the phase detector (PD), which is primarily responsible for generating a signal containing the phase error information, the loop filter (LF),also called loop controller, which drives the phase error signal to zero and the voltage controlled oscillator (V_{CO}), which produces a synchronized unit vector in its output.

The PLL performs phase and frequency tracking to provide a reference signal to synchronize it with the grid voltage, thus reducing unwanted frequency variations. As soon as this loop detects a variation in the angle between the two signals (that is, a variation in frequency), It reacts quickly and precisely to resynchronize them. The voltage outputs V_d and V_q of the current regulator are converted into three reference modulation signals Uabc used by the PWM generator [67].

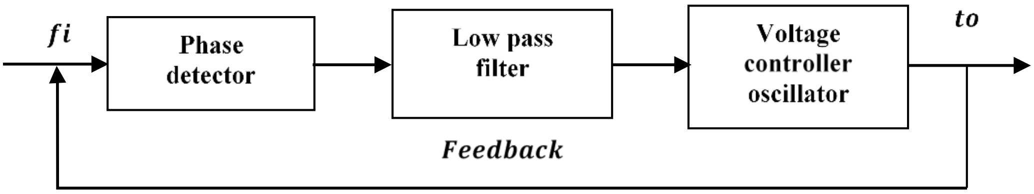


Figure 3.11: Block diagram of the PPL

3.8. Grid side control

PV array with boost DC-DC inverter are connected to the ac grid via a DC/AC inverter. The inverter is employed to step down and to modulate the output voltage according to the grid voltage. Finally, the filter is designed to reduce high-order harmonics introduced by the PWM modulation of the DC/AC converter. The control strategy mainly consists of the DC/AC converter is designed to supply current into the utility line by regulating the bus voltage to 400V. The control of the power flow to the grid, according to the proposed power systems, is based on the control of active and reactive power. In the power DC-AC converters, active and reactive power from the grid-side inverter can be given by:

$$\begin{cases} P = V_a.i_a + V_b.i_b + V_c.i_c \\ Q = \frac{1}{\sqrt{3}}(V_{ab}.i_c + V_{bc}.i_a + V_{ca}.i_b) \end{cases} \quad (3.11)$$

Where, V_a , V_b , V_c are three-phase voltages at the AC bus,i_a, i_b , i_c are three-phase currents injected into the AC grid. Applying Park transformation, Eq. (7) can be written as:

$$P=\frac{3}{2}(V_d.i_d+V_q.i_q)$$
$$Q=\frac{3}{2}(V_q.i_d-V_d.i_q) \tag{3.12}$$

Where V_q ,V_d represent the d,q components of the voltage at connection point i_q, i_d represent d q components of the line current. In the reference frame synchronized with the grid voltage,

$V_q = 0$, $V_d = V$,so:

$$P = \frac{3}{2}.V_d.i_d \tag{3.13}$$

$$Q = -\frac{3}{2}.V_d.i_q \tag{3.14}$$

The inverter uses hysteresis switching and controls active power by manipulation of direct-axis current while holding reactive power at 0 VAR.

$$i_{d,ref} = \left\{k_{d,p} + \frac{k_{d,i}}{s}\right\}.(V_{dc,ref} - V_{dc}) \tag{3.15}$$

$$i_{q,ref} = -\left\{k_{q,p} + \frac{k_{q,i}}{s}\right\}.(Q_{dc,ref} - Q) \tag{3.16}$$

The vector control of the current is performed using the referential Park synchronized with the grid voltage. The electric filter equations (R_f, L_f) can be simplified in this reference as follows:

$$\begin{cases} V_{dg} = V_d - \left[L_f \times \frac{di_d}{dt} + R_f \times i_d\right] + \omega \times L_f \times i_q \\ V_{qg} = V_q - \left[L_f \times \frac{di_q}{dt} + R_f \times i_q\right] - \omega \times L_f \times i_d \end{cases} \tag{3.17}$$

Where, ω, is the grid frequency.

The current controller still uses PI regulator, described by:

$$V_{d,ref} = V_d + \left\{k'_{d,p} + \frac{k'_{d,i}}{s}\right\}.\left(i_{d,ref} - i_d\right) - \omega.L.i_q \tag{3.18}$$

$$V_{q,ref} = V_q + \left\{k'_{q,p} + \frac{k'_{q,i}}{s}\right\}.\left(i_{d,ref} - i_q\right) - \omega.L.i_d \tag{3.19}$$

Figure 12 shows the diagram of the control current of the grid-side converter in the referential Park. It consists of three stages: correction, compensation and decoupling.

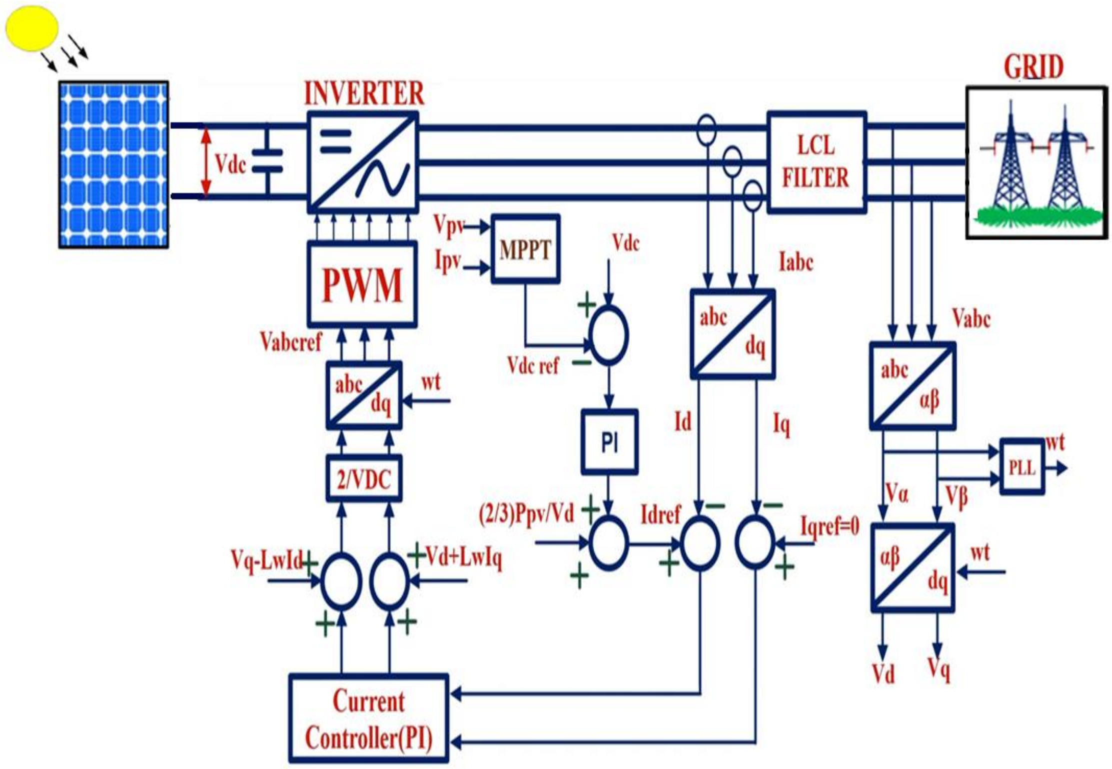


Figure 3.12: Control structure of PV connected grid

3.9. Conclusion

For optimal performance, the connection between the PV system and the grid (or receiver) requires the insertion of static converters between the two. This chapter was devoted to the state of the art of static converters. First, we began with general information on inverters, their types, classifications, selection criteria and the different architectures of inverters connected to the electrical grid.

Then the mathematical modeling of the three-phase voltage inverter, we gave its operating principle with its power diagram, as well as the triangular-sinusoidal PWM control technique. Next, we modeled the DC bus and the PLL synchronization loop. Finally, we finished by modeling the chosen grid.

CHAPTER 4: SIMULATION AND RESULTS OF THE PROPOSED GRID-CONNECTED PV SYSTEM

4.1. Introduction

This chapter focuses on the simulation and presentation of the results of the proposed grid-connected PV system (Figure 4.1). The simulation is performed using MATLAB-Simulink, which allows us to simulate our system, including the PV system, the boost converter, the voltage inverter with the MPPT algorithm, and the active and reactive power control of the grid-side inverter and the power grid.

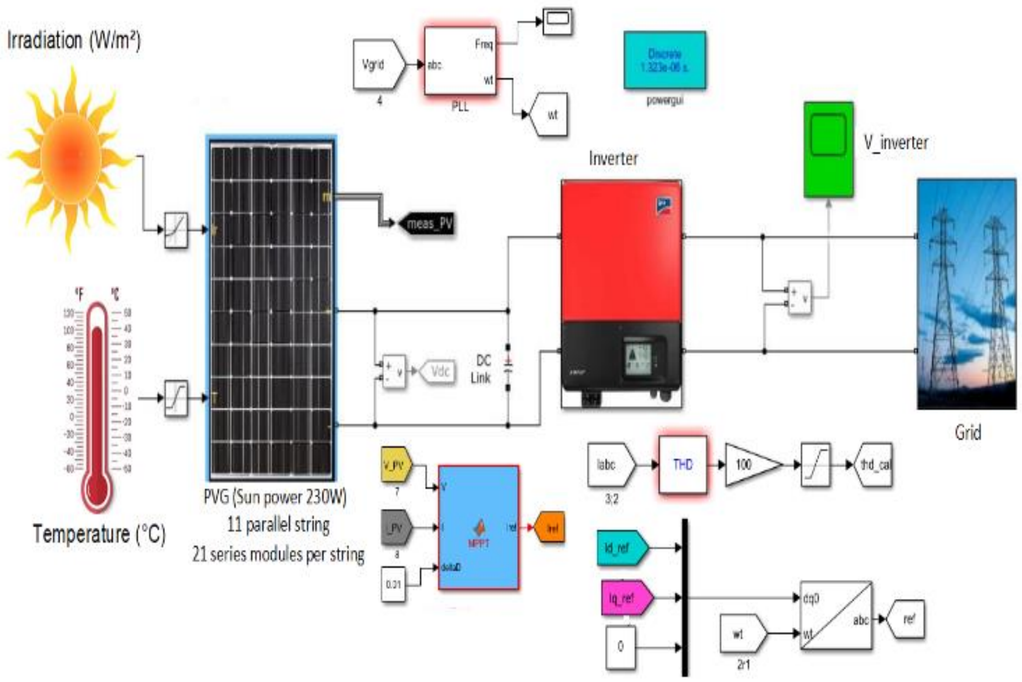


Figure 4.1 : système PV connecté au réseau dans Matlab Simulink

To meet the required output of 53 kW, a photovoltaic generator composed of 231 panels is implemented, configured in 21 panels connected in series and 11 parallel strings. This series-parallel topology is designed to provide the appropriate voltage and current levels to match the system’s operational needs.

Each panel delivers a maximum power of 230.04 W, with a maximum power voltage of 40.5 V and a maximum power current of 5.68 A. The series connection ensures a sufficiently high DC voltage, while the parallel branches significantly increase the current capacity.

This configuration allows the photovoltaic array to operate efficiently, ensuring stable power production and seamless integration with the power converter and the grid.

Table 4.1: Characteristics of GPV and PV panel

Grandeur	Valeurs
Maximum power module (P_{max})	230.04 W
Short circuit current (I_{sc})	6.05 A
Open circuit voltage (V_{oc})	48.2 V
Number of cells (N_s)	72
Maximum power current (I_{mp})	5.68 A
Maximum power voltage (V_{mp})	40.5 V
Parralell string	11
Series-connected modules per string	21
The power of the PVG	**53 kWc**
Temperature coefficient of Voc (%/deg.C)	-0.31
Temperature coefficient of Isc (%/deg.C)	0.016

The I-V and P-V curves of the previous PV panel are presented in Figure (4.1), which clearly shows that the electrical characteristics are identical to those given in the table (4.1).

4.2. The variable of solar irradiations

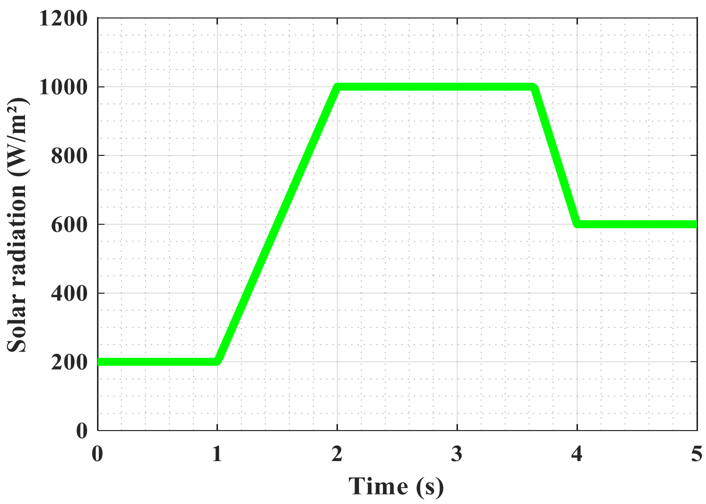


Figure 4.2 .Variable solar irradiations

Variable solar irradiations were applied to the system. Figure (4.2) distributed over five time intervals as follows:

- From 0 to 1 second, the solar irradiation is 200 W/m²;
- From 1 to 2 seconds, the solar irradiation is 200 to 1000 W/m²,
- From 2 to 3.6 seconds, the solar irradiation is 1000 W/m²;
- From 3.6 to 4 seconds, the solar irradiation is 1000 to 600 W/m²,
- From 4 to 5 seconds, the solar irradiation is 600 W/m².

4.3. The DC bus voltage

It is essential to maintain a constant DC bus voltage despite the variable current flowing into the DC bus capacitor. The curve illustrates the temporal profile of the voltage at the terminals of the PVG over a 5 second interval.

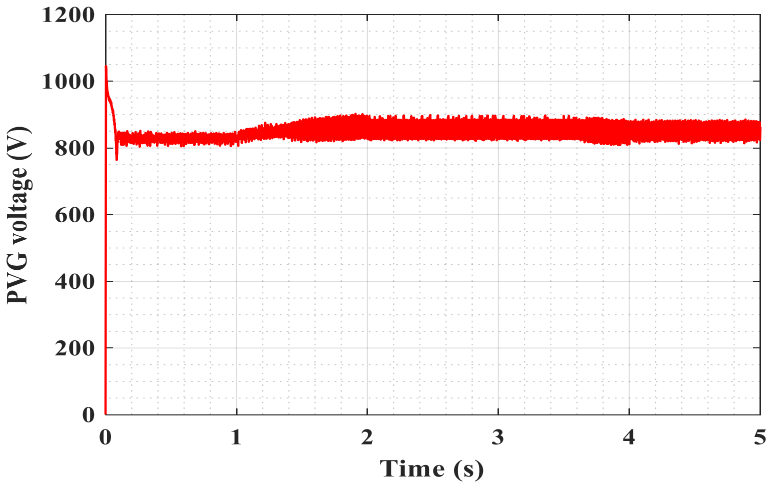


Figure 4.3.The voltage across the PVG

A noticeable initial voltage drop occurs near time zero, likely due to system start-up transients or load connection effects. This is followed by a gradual stabilization around 820 V, indicating that the system quickly reaches a steady operating state.

The overall voltage stability observed after the transient period suggests that the PVG operates under relatively constant irradiation conditions. The high and steady voltage level is characteristic of a series-connected panel configuration, which allows the system to generate sufficient voltage to drive downstream components such as inverters or DC-DC converters.

This voltage behavior confirms that the generator is functioning within its intended operating range and that the electrical load is well matched to the PVG output.

4.4. The PVG current

The currents are almost sinusoidal and reflect the values of the extracted current from the PV generator. Figure 4.4 illustrates the fluctuations in current injected by the photovoltaic (PV) system throughout the day, primarily due to variations in solar irradiation. To address these fluctuations and ensure consistent current delivery to the sinusoidal grid, a proportional-integral (PI) current regulator is employed. This regulator enhances the system's dynamic performance, especially under rapidly changing atmospheric conditions.

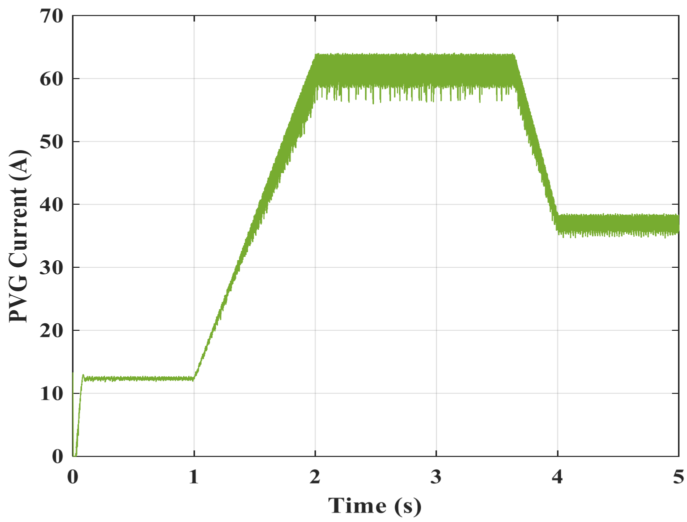


Figure 4.4 PVG current

The injected current distributed over five time intervals. For the first interval (200 W/m²), the current is equal to 13 A; then for the second interval varies from 1 to 2 seconds, the current is varies between 13 to 62 A, and for the third interval (1000 W/m²), the current is equal to 62.5 A. For the fourth interval varies from 3.6 to 4 seconds, the current varies between 62.5 to 37 A and for the last interval (600 W/m²) the current is equal to 37 A.

The time profile of the current generated by the PVG directly reflects the variations in photovoltaic production, which are primarily influenced by solar irradiation conditions. This current is not constant; it fluctuates in response to the amount of sunlight received by the solar panels, translating the natural variability of the solar resource throughout the day. These fluctuations in current clearly illustrate the dynamic nature of solar energy, which depends on environmental factors such as cloud cover, atmospheric conditions, and the sun's position.

4.5. The power generated by the PVG

We see that with each variation in irradiance, the MPPT controller tracks maximum power by regulating the photovoltaic voltage to extract the maximum output. Figure (4.5) shows the evolution of the output PVG power.

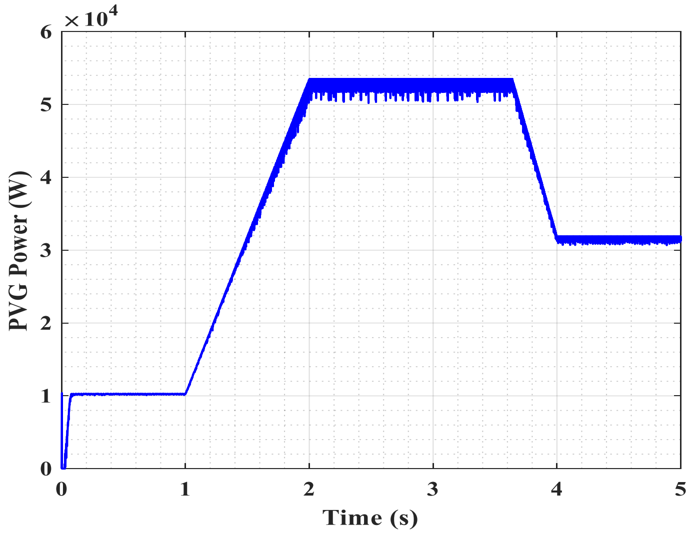


Figure 4.5 Power generated by the PVG

Figure (4.5) distributed over five time intervals. For the first interval (200 W/m²), the output power is equal to 10 kW; then for the second, the solar irradiation increase, so the output power is proportional the variation of solar radiation. For the third interval (1000 W/m²), the output power is equal to 53 kW, then the fourth interval, the solar irradiation decrease, so the output power is decrease, and for the last interval (600 W/m²) the output power is equal to 32 kW.

The power generated by the PVG logically follows its current and voltage profile. Increasing, maintaining, and decreasing the PVG power are the drivers of the changes observed in the system's active power.

4.6. The THD

Figures 4.6 and 4.7 illustrate the fluctuations in current THD and voltage THD due to variations in solar irradiation. The current THD varies between 1.6% and 2.4% for strong irradiations, however it equals to 7% for a low solar radiations. This shows that the MPPT controller has difficulty tracking the MPP in low irradiations conditions. The voltage THD is almost constant, equal to 0.08%, a very acceptable value of <1% (preferred standard) regardless of the variation in solar irradiation, which clearly shows that illumination affects the PVG current.

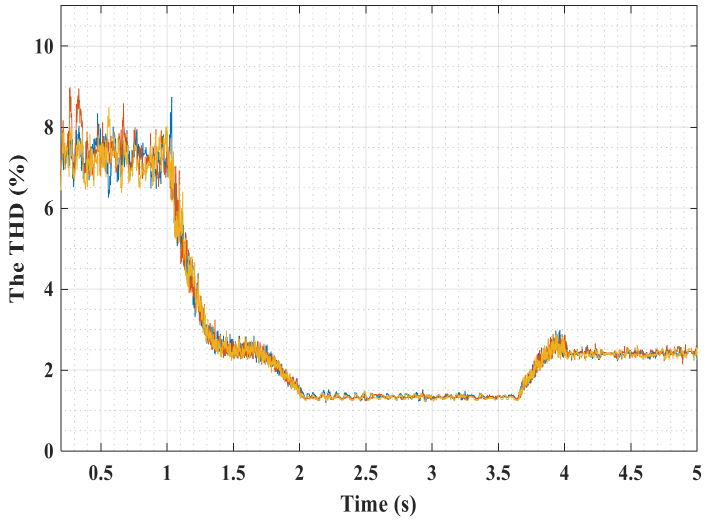


Figure 4.6. The current THD

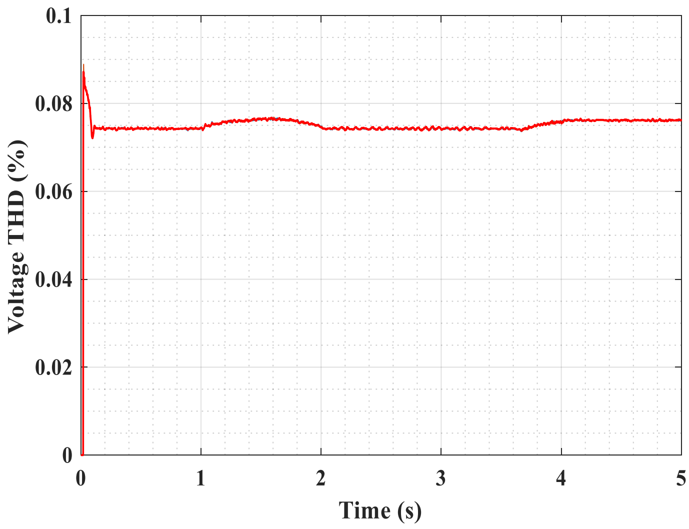


Figure 4.7. The voltage THD

The control blocks improves the quality of the voltage and current of the photovoltaic system injected into the grid and makes it possible to obtain a low THD.

4.7. The grid frequency stability

Maintaining voltage and frequency levels of the PV system's output that closely match those of the grid is crucial. This alignment underscores the importance of the current and voltage control loops, the pulse-width modulation (PWM) generator, and the phase-locked loop (PLL). Together, these components adjust power flow and refine the waveform quality fed into the grid, ensuring efficient and stable integration of solar energy.

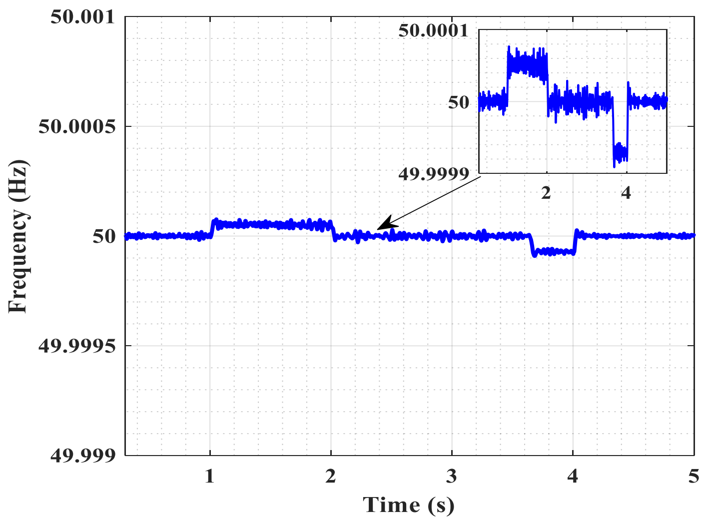


Figure 4.8 Inverter Frequency Stability

The remarkable stability of the frequency around 50 Hz, despite the significant fluctuations in PVG production and active power, demonstrates the robustness of the system's frequency control. The minimal variations observed (around 2 seconds) could be due to momentary imbalances between supply and demand, quickly corrected by the control system.

4.8. The three-phase output currents

The amplitude of the three-phase output currents (Ia, Ib, Ic) faithfully follows the active power curve. As the active power increases, the currents increase proportionally to provide this power.

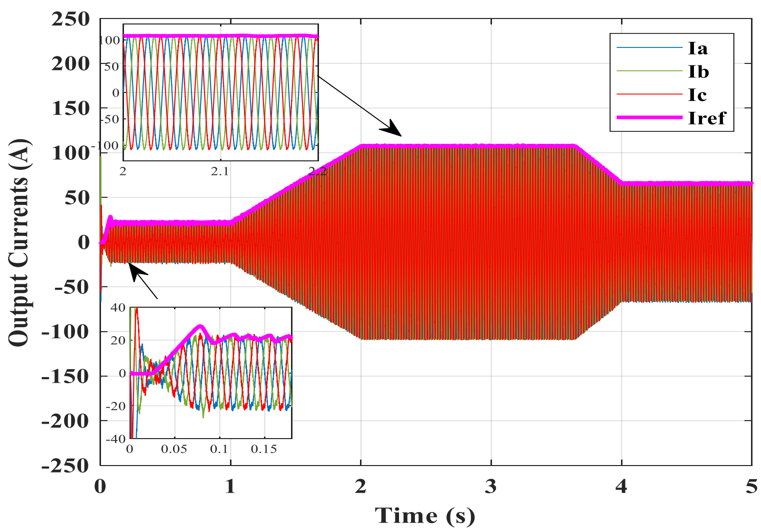


Figure 4.9 the three-phase output currents

The reference current (I_{ref}) is clearly the set point followed by the output currents, indicating a high-performance current control system.

4.9. Active and reactive power

Figure (4.10) illustrates the injected active power and reactive power respectively. The injected active power corresponds to the power extracted from the photovoltaic generator. The increase in active power coincides precisely with the increase in PVG power, indicating that PVG is the main source of energy injected into the system during this period.

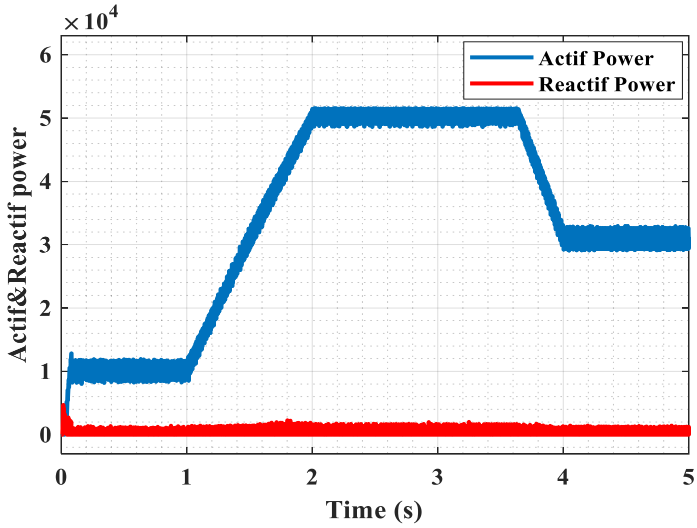


Figure 4.10. Active and reactive power

However, maintaining reactive power close to zero suggests active power factor control, optimizing energy transfer efficiency and minimizing reactive losses in the system.

4.10. The output voltage

The stability of the output voltage (around 320 V) despite variations in active power and PVG production highlights the effectiveness of the system's voltage control. The inset shows the sinusoidal and balanced nature of the three-phase voltages.

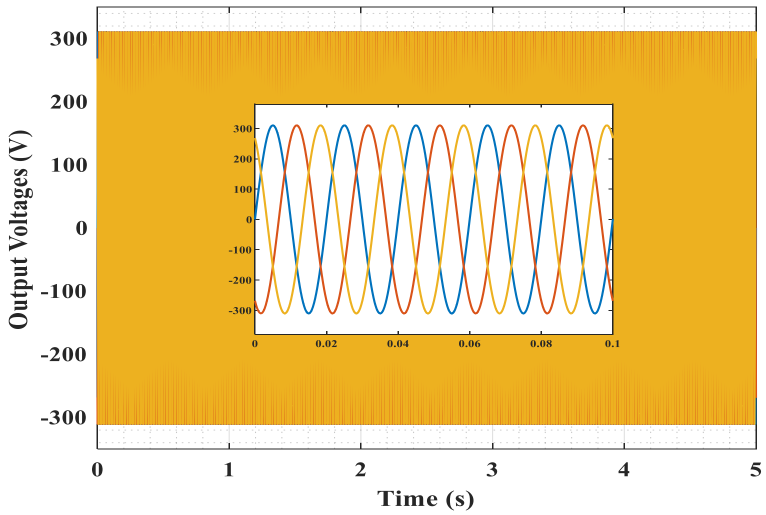


Figure. 4.11. Output voltage

The results indicate an electrical system where solar energy, captured by the PVG, is efficiently integrated and distributed. The overall control system manages to maintain the stability of essential grid parameters (frequency and output voltage) while optimizing the transfer of active power generated by the renewable source. Reactive power management is also well controlled.

4.11. Conclusion

These graphs depict a resilient and well-controlled electrical system, capable of managing fluctuations in the output of a renewable energy source such as a photovoltaic generator, while ensuring stable and efficient operation for connected loads or the main grid. The PVG production cycle (rise, plateau, and decline). This clearly affects the system's active power and output currents, but frequency and voltage are kept within acceptable limits thanks to appropriate regulation mechanisms.

General conclusion

In this work, we studied and modeled a grid-connected PV system, focusing on the key elements that ensure reliable and efficient electricity production from solar energy. The objective of this thesis was to provide a thorough understanding of the various components of the PV system, their operation, and their interaction with the electrical grid, with a view to optimizing performance and ensuring compatibility with grid requirements.

We first laid the foundations of our study by presenting a state-of-the-art overview of PV systems, their development, and existing technologies. By focusing on global energy challenges and the energy situation in Algeria, we highlighted the growing importance of renewable energies, particularly solar energy, in the global energy transition. This chapter also provided an opportunity to discuss Algeria's solar potential, a major asset for the country's energy future.

We then described the modeling of the components of a grid-connected PV system. We began by modeling the PVG, its electrical characteristics, and the influence of climatic conditions (sunlight, temperature) on the performance of the PVG. We also studied maximum power point tracking (MPPT) techniques, including the P&O method,This is a crucial element for optimizing energy production based on variations in sunlight. The DC-DC Boost converter, essential for adapting the voltage between the PVG and the inverter, was also modeled, allowing for a better understanding of the interactions between the various system components.

We then addressed the practical aspects related to the inverter's influence on the grid and vice versa. By detailing the different types of inverters (centralized, string, and modular), we highlighted the selection criteria needed to choose the most suitable technology based on the system's characteristics. We also studied grid-side control techniques, ensuring stable and compliant power injection. The inverter plays a central role in managing compatibility between PV production and the electricity grid, and it is essential that it operate optimally to avoid any disruptions.

Finally, our system allowed us to validate the theoretical models developed using simulations in MATLAB/Simulink. These simulations demonstrated the impact of sunlight variations on PV energy production, as well as the effectiveness of maximum power point tracking. They also allowed us to evaluate the inverter's performance when feeding energy into the grid. This simulation step is crucial for testing the system before its actual deployment, as it allows for identifying weak points and optimizing the system based on the results obtained.

Simulation results also showed that grid-connected PV systems can operate reliably and efficiently under variable climatic conditions. However, for large-scale implementation, further research is needed to improve the management of the interaction between the PVG and the grid, particularly with regard to grid stability and the integration of energy storage systems. Optimizing energy injection into the grid and managing fluctuations in PV production remain significant challenges.

In the Algerian context, this work paves the way for further exploitation of solar potential, a strategic sector for the country due to its abundant natural resources. The development of grid-connected PV systems could play a key role in diversifying energy production and reducing dependence on fossil fuels. The implementation of appropriate incentive policies and regulations is essential to accelerate the adoption of these technologies and ensure their long-term success.

In conclusion, this thesis provides essential elements for understanding, modeling, and optimizing grid-connected PV systems. The results validate theoretical concepts and open up opportunities for real-world applications. However, much remains to be done to improve the performance and integration of PV systems into electrical grids, particularly with regard to energy efficiency, intermittency management, and the use of storage technologies.

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وزارة التعليم العالي والبحث العلمي

Université de Ghardaïa — جامعة غرداية

Faculté des Sciences et de la Technologie كليـة العلوم والتكنولوجيـا

قسم: الآلية والكهرو ميكانيك
شعبة: الكهرو تقني
تخصص: طاقات المتجددة في الكهرو تقني

غرداية في: 2025/07/04

شهادة ترخيص بالتصحيح والايداع:

أنا الأستاذ :مدوكالي حمزة
بصفتي المشرف المسؤول عن تصحيح مذكرة تخرج (ماستر) المعنونة بـــ:
Étude et Optimisation d'une centrale PV connectée au réseau électrique
من انجاز الطالبين:
بوحادة عبدالقيوم
غزيل وليد
التي نوقشت بتاريخ :2025/06/11

أشهد أن الطالبين قد قاما بالتعديلات والتصحيحات المطلوبة من طرف لجنة المناقشة وقد تم التحقق من ذلك من طرفنا وقد استوفت جميع الشروط المطلوبة.

امضاء المسؤول عن التصحيح

مدوكالي حمزة

حمزة مدوكالي

مصادقة رئيس القسم

رئيس قسم الآلية والكهروميكانيك
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