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by:

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Title

Design and PIL implementation of grid-connected photovoltaic system

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بسم الله الرحمن الرحيم

THANKS

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DEDICATION

To my beloved **parents**, whose unwavering love, encouragement, and sacrifices have been the cornerstone of my journey. Your support has been my guiding light, and this thesis is a testament to your belief in me. I dedicate this work to you, with heartfelt gratitude and love.

To my dear two brothers **anouar** and **ziyad**

"May God protect them"

To all my **family** and my all **friends**

LOUAIL chaima

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BOUGANDOURA racha

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General introduction

Due to escalating fuel prices and mounting environmental concerns, renewable energies have emerged as pivotal sources for supplying electricity to both residential and industrial sectors. Power generation from renewable sources offers numerous benefits, including cleanliness and inexhaustibility. Wind, hydro, geothermal, and solar energies have been accessible since the inception of our planet and have been harnessed by early human civilizations in various capacities.

In contemporary times, the exploitation of these energy sources has seen significant advancements, leveraging accelerated technological progress. Solar energy, in particular, is recognized as a rapidly evolving technology, witnessing a substantial reduction in equipment costs. Specifically, photovoltaic-based power sources have already demonstrated their efficacy in both grid-connected and stand-alone systems. Moreover, they are hailed as promising solutions for mitigating greenhouse gas emissions. Consequently, their environmentally friendly attributes, abundance, and ongoing cost reductions have spurred their widespread adoption globally. Despite the inherent advantages of photovoltaic power generation.[1]

Solar energy is obtained directly from the sun's radiation and can be converted into electrical energy through the photovoltaic effect. Photovoltaic panels are composed of cells capable of converting photons into electrons, thereby generating electricity in the form of direct current (DC).

In this dissertation ,our study centers on the photovoltaic industry, with a primary emphasis on modeling and controlling grid-connected photovoltaic systems.[2]

Our work is organized into three chapters as follows:

The first chapter serves as an introduction to the photovoltaic system. It commences with an overview of photovoltaic energy, elaborating on the photovoltaic effect and the fundamental principles of photovoltaic conversion. Subsequently, various types of photovoltaic cells are examined, along with their characteristics and modeling methodologies. The subsequent section delves into the concept of a photovoltaic generator, analyzing the impact of sunlight and temperature variations on its performance. Furthermore, the chapter addresses the components comprising a photovoltaic system, while also providing an overview of its classification. Conclusively, it discusses the quality standards associated with grid-connected systems and provides a comprehensive assessment of the advantages and disadvantages of PV systems.

Chapter two focuses on the control of converters in grid-connected photovoltaic systems. It commences with an exploration of the configuration of grid-connected photovoltaic generation, followed by an examination of various types and classifications of converters, specifically DC-DC converters. The chapter then delves into the structure, classification, and modeling of three-phase inverters. In the third section of this chapter, the principle and characteristics of pulse width modulation (PWM) control are discussed. Subsequently, an introduction to Maximum Power Point Tracking (MPPT) control is provided, covering its definition, methods, and the characteristics of different MPPT methods the chapter wraps up by addressing the voltage source inverters (VSI) control and employing the Phase-Locked Loop (PLL) method for synchronization.

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The concluding chapter focuses on the simulation and findings of the investigated system. It commences with presenting the simulation outcomes related to the panel characteristics and the photovoltaic generator. Subsequently, it discusses the results of the boost converter control using the Perturb and Observe (P&O) algorithm. Furthermore, it examines the simulation findings concerning the inverter with Voltage Source Inverter (VSI) control. This chapter will wrap up with an overview of the simulation results of the entire photovoltaic system interconnected with the grid.in the end, we connected the system to the LAUNCHPAD F and extracted the results. .

Finally, the work will be summarized with a general conclusion.

Chapter1 : Photovoltaic system

Introduction of Photovoltaic System

Each day, the sun provides the Earth with a plentiful supply of energy. This vast resource can be efficiently tapped into using photovoltaic technology, which converts solar energy into electricity. Photovoltaic (PV) technology, often referred to as solar electric, is acknowledged as one of the most progressive and rapidly growing renewable energy sources utilized worldwide for electricity generation. Embracing PV technology presents numerous benefits, such as its sustainable nature, widespread accessibility, environmental friendliness, cost-effectiveness, lack of pollution, and minimal maintenance needs.[3]

Photovoltaic modules or panels are composed of semiconductors that allow for the direct conversion of sunlight into electricity. These modules prove to be a safe, reliable, maintenance-free, and non-polluting source of electrical energy. The majority of solar modules available on the market today come with warranties of over 20 years, and they will continue to function well beyond this period.[4]

Millions of systems have been installed worldwide, with varying power capacities ranging from fractions of a watt to several megawatts. For many applications, electric solar systems are not only cost-effective but also can represent the least expensive option. [4]

This chapter is dedicated to introducing photovoltaic systems. We begin by defining photovoltaic energy and elucidating the photovoltaic effect. We delve into the principle of photovoltaic conversion, discussing various types and characteristics of photovoltaic cells. Additionally, we explore the modeling of photovoltaic cells and the generator model for photovoltaic (PV) systems. Furthermore, we examine the classification and components of PV systems, as well as the quality standards for grid-connected systems. Lastly, we conclude by outlining the advantages and disadvantages of photovoltaic systems.

1.1 Photovoltaic energy

1.1.1 Definition

Each day, the sun generously supplies Earth with energy. Humans can harness this abundant and free energy using a technology known as photovoltaics. The term photovoltaics (PV) was initially coined around 1890, derived from the Greek words "photo," meaning light, and "volt," referring to electricity. This term precisely describes the photovoltaic phenomenon, wherein light is directly converted into electricity.[5]

Photovoltaic (PV) energy is a clean, renewable source of energy that utilizes solar radiation to generate electricity. It operates on the principle of the photoelectric effect, whereby certain materials can absorb photons (light particles) and release electrons, thereby generating an electric current. To achieve this, a semiconductor device known as a PV cell is utilized. PV cells can be fabricated from monocrystalline silicon, which typically achieves a maximum efficiency between 18% and 20% on average. Alternatively, they can be made from polycrystalline silicon, with an average efficiency ranging between 16% and 17.5%, and this option tends to be more cost-effective compared to monocrystalline silicon PV cells. PV cells can also be composed of amorphous silicon, although this type exhibits a disordered crystalline structure, resulting in lower performance (with an average efficiency between 8% and 9%). The electrical output obtained from a PV cell is direct current (DC), typically with a voltage around 0.5 volts. Consequently, PV cells are arranged in series and/or parallel configurations to form a photovoltaic panel. Series grouping increases the operating voltage, while parallel grouping increases the current flow .[5]

1.2The photovoltaic effect

The evolution of the photovoltaic effect from an intriguing scientific phenomenon to one of the most efficient methods for directly converting solar energy into electrical energy is outlined.

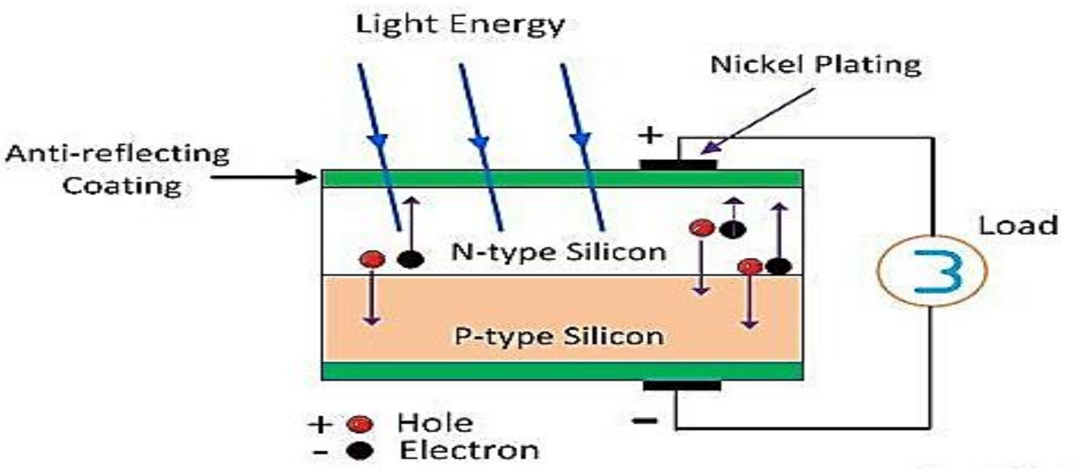
TInitially discovered by Edmond Becquerel during experiments with wet cells, he observed that the voltage of the cell increased when its silver plates were exposed to sunlight.[6]

1.3 The principle of photovoltaic conversion

Photovoltaic cells harness the photoelectric effect to produce direct current by absorbing solar radiation. This effect enables cells to directly convert the light energy from photons into electricity through a semiconductor material carrying electric charges.

A photovoltaic cell is composed of two types of semiconductor materials, one with an excess of electrons and the other with a deficit of electrons. These two parts are respectively referred to as "doped" n-type and p-type. Doping silicon crystals involves adding other atoms to enhance the material's conductivity.

A silicon atom has 4 outer electrons. One layer of the cell is doped with phosphorus atoms, which have 5 electrons (1 more than silicon). This doping is referred to as n-type doping because electrons (negatively charged) are in excess. The other layer is doped with boron atoms, which have 3 electrons (1 less than silicon). This type of doping is called p-type doping due to the electron deficiency created. When the first layer is brought into contact with the second, the excess electrons in the n-material diffuse into the p-material.[7]



1.1: photovoltaic cell structure

1.3.1 Type of photovoltaic cells

1.3.1.1 Monocrystalline Silicon(a)

There are two methods by which it is possible to obtain electronic-grade monocrystalline silicon: the Czochralski (CZ) method and the Float Zone (FZ) method, but they require considerable energy expenditure. The silicon obtained allows for achieving record conversion efficiencies in the laboratory, on the order of 25% .The drawback of this technology is the prohibitive cost of material production.[18]

1.3.1.2 Polycrystalline Silicon(b)

Polycrystalline silicon is produced using growth techniques that ensure the formation of a columnar structure with large crystals (referred to as multicrystalline silicon) to limit the adverse effects of grain boundaries. Industrial conversion efficiencies, which were around 8 to 10% before 1980, currently reach 16 to 17% for (large) wafers of 200 cm^2. This is the most widely represented technology in the photovoltaic market because it combines high conversion efficiencies with low production costs compared to monocrystalline silicon.[18]

1.3.1.3 Amorphous silicon(c)

The utilization of amorphous silicon in solar cells has presented notable advantages in terms of both electrical properties and manufacturing processes. It provides a straightforward production method, low energy consumption, cost-effectiveness, and the capacity to fabricate cells with substantial surface areas. Nevertheless, despite the decreased production costs, amorphous silicon solar cells come with two drawbacks. Firstly, they demonstrate lower conversion efficiency in comparison to monocrystalline and polycrystalline silicon cells. Secondly, their performance experiences a rapid decline of 10% to 20% in power output during the initial three to six months of operation.[19]

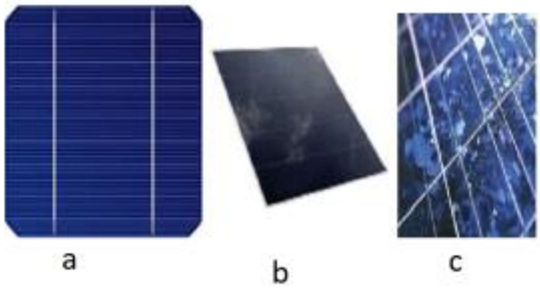


Figure 1.2 :Type of photovoltaic cells [19]

1.3.2 Electrical characteristics of photovoltaic cells

The electrical characteristics of a photovoltaic cell can be described by few parameters:

1. **Short-circuit current Isc (for Voc= 0):** This refers to the current obtained by short-circuiting the terminals of the cell (taking V= 0 in the equivalent circuit). It increases linearly with the intensity of cell illumination and depends on the illuminated surface area, the wavelength of the radiation, the mobility of carriers, and the temperature.[8]
2. **Open circuit voltage Voc (for Isc = 0):** Voc is the open circuit voltage, which is the maximum voltage that can be obtained from the solar cell. Since the junction of the solar cell is biased by the current generated by the light, the open circuit voltage is similar to the amount of direct biasing on the solar cell.
3. **Maximum Power Point (MPP):** The power generated by a PV cell is determined by multiplying the voltage and the current at its terminals. This output power is zero at both the short-circuit and open-circuit points since the voltage and current outputs are zero, respectively, in these scenarios. Between these two extremes, the power generated by the PV cell is positive.

A significant feature of the PV cell's electrical characteristic is the point where the power output reaches its maximum value. This point is referred to as the Maximum Power Point (MPP), with the corresponding voltage and current typically denoted as VPM and IPM, respectively.[9]

$$P_{mp} = V_{mp} I_{mp} \qquad (1.1)$$

Where:

P_{mp}= maximum power point,

V_{mp}= maximum power voltage,

I_{mp}= maximum power current.

4. Fill factor (FF):

The Fill Factor (FF) of a PV cell is a quality factor related to the efficiency of the cell. It isdefined as the ratio of the maximum power to the product of V_{oc} and I_{cc} [9]:

$$FF = \frac{P_{PM}}{V_{CO} I_{CC}} = \frac{V_{PM} I_{PM}}{V_{co} I_{cc}} \qquad (1.2)$$

Where:

Vco = open circuit voltage,

Icc = short circuit current.

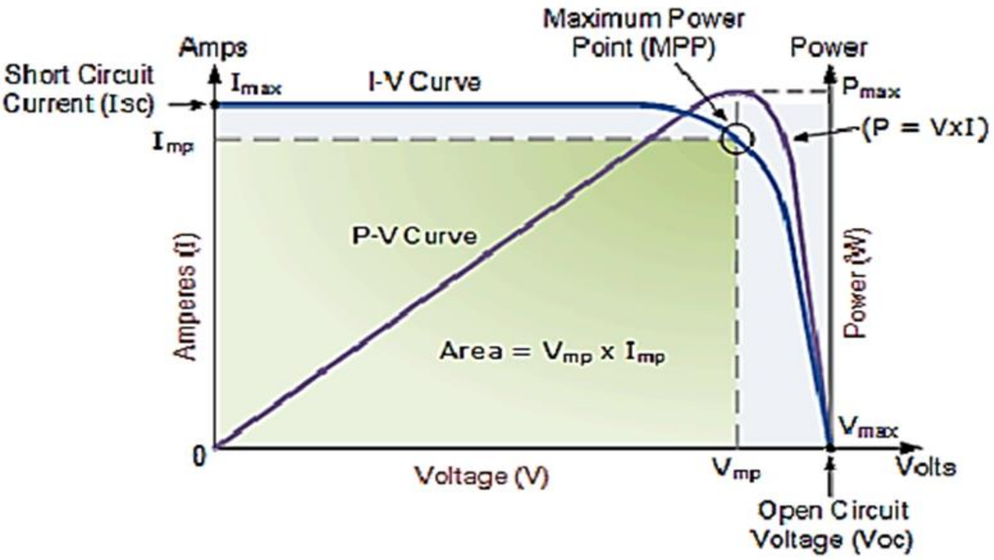


Figure 1.3. Typical I-V characteristics of photovoltaic cell

1.3.3 Modeling of photovoltaic cells

This section provides a brief description of the theory of the PV model under study; the following nomenclature is used throughout the document to ensure consistency.

The single-diode model is historically the first PV model, initially developed for monocrystalline silicon PV cells, but it remains the most commonly used to this day due to its simplicity. Other more sophisticated models involve two or three diodes for increased accuracy under low irradiance conditions, and sometimes additional voltage-dependent current sources to account for breakdown operation or recombination phenomena in certain thin-film technologies.

This document is limited to the single-diode model, as it is the PV model upon which the majority of non-iterative parameter extraction methods rely, and evaluates its effectiveness across all commercial PV technologies, including monocrystalline/multicrystalline silicon and thin film.

This model consists of an equivalent circuit illustrated in Figure (1.3) and a set of five parameters:

[I_{ph}, I_s, R_S, R_{Sh}]. [10]

-The photo current I_{ph}.

-The diode saturation current Is - The series resistance $R_{S.}$

- The shunt resistance R_{Sh}

Its equivalent circuit model is primarily used to monitor and evaluate PV performance and explore various MPPT techniques.

The equivalent circuit of the general model consists of a photocurrent source, a diode, a parallel resistance representing the leakage current, and a series resistance describing the internal current resistance.

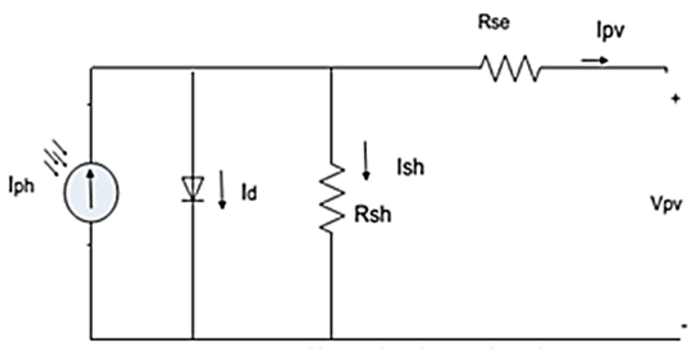


Figure 1.4: Equivalent circuit of a PV cell

The characteristic equation of a PV cell is given as follows:

$$I = I_{ph} - I_S\left(exp\left[\frac{q(v+IR_S)}{KTA}\right] - 1\right) - \frac{(v+IR_S)}{R_{Sh}} \quad (1.3)$$

Where:

I_{ph} is a current or photocurrent generated by light, $I_s$is the cell saturation current,

q = (1.6 x10 $^{-19}$C) is the electron charge, **k** (= 1.38.10^{-23} J/K) is the Boltzmann constant, **T** is the operating temperature of the cell, **A** is the ideality factor, R_{Sh} is the shunt resistance, and R_S is the series resistance.

The photocurrent mainly depends on solar insolation and the operating temperature of the cell, which is given as:

$$I_{ph} = \lambda(I_{sc} + K_1 (T - T_r)) \quad (1.4)$$

Where I_{sc} is the cell short-circuit current at 25°C and 1 kW/m^2, K_1 is the temperature coefficient of the cell short-circuit current, $T_r$is the reference temperature of the cell, and **λ** is the solar insolation in kW/m^2. On the other hand, the cell saturation current varies with the cell temperature, which is described as:

$$I_S = I_{RS}\left(\frac{T}{T_r}\right)^3 exp\left[qE_G\frac{\left(\frac{1}{T_r}-\frac{1}{T}\right)}{KA}\right] \quad (1.5)$$

Where I_{RS} is the reverse saturation current of the cell at a reference temperature and solar radiation, E_G is the band-gap energy of the semiconductor used in the cell. The ideality factor **A** depends on the PV technology. The reverse saturation current at the reference temperature can be approximately obtained as follows:

$$I_{RS} = \frac{I_{SC}}{exp\left[\frac{qv_{oc}}{N_S KAT}\right]-1} \quad (1.6)$$

1.4. The characteristics of the modules

The photovoltaic solar panel, being an assembly of solar cells, its I(V) characteristic is directly linked to that of the basic cell. It is characterized by the open-circuit voltage Vco and the short-circuit current Icc.

The energy provided by a module will therefore depend on:

- The type of photovoltaic cell chosen.
- The number of cells connected in series on this panel.

The number of electrons released by a cell, for a given unit of time, depends on the photon flux reaching it, whereas the output current of a solar panel will therefore depend on:

- The sunlight intensity.
- The orientation of the module relative to the sun (a panel perpendicular to the sun's rays receivesthe greatest photon flux).
- The number of parallel cell circuits.

The voltage across a module, as well as the electrical power it provides, is therefore strongly determined by the manufacturer's choice (number of cells in series and panel dimensions).

The maximum power is obtained at a point that depends on the temperature and the intensity of the illumination; it is expressed in peak watts (Wp) and is used to determine the nominal efficiency of the panel.

The efficiency of the module is the efficiency of a cell reduced by losses due to the connections between cells, the transparency of encapsulation materials, and potentially the voltage drop in the "blocking" diode when it is necessary to protect the battery from potential nighttime discharge.

$$\eta_{module} = \eta_{cell} \times \eta_{conection} \times \eta_{encapsulation} \times \eta_{diode} \quad (1.7)$$

The temperature coefficient indicates the loss of power of the panel as a function of the temperature increase. Typical value, -0.45% /°C /cell.

A panel has a minimum warranty of 20 years with a reduction in maximum output power during this period of 10%.[11]

1.5 Influence of irradiation and temperature on the PV module

1.5.1 Influence of irradiation

By varying the illumination between 400 W/m² and 1000 W/m² with a step of 200, the characteristic (Ipv = (Vpv)) is given by the figures (1.4). It is noted that the value of the short-circuit current is directly proportional to the intensity of the radiation. However, the open-circuit voltage does not vary in the same proportions; it remains almost identical even at low illumination levels.[12]

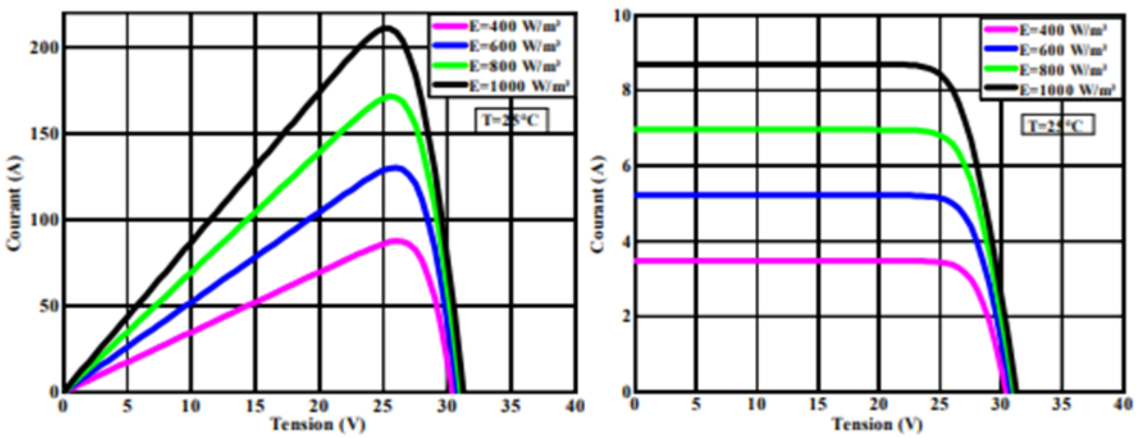


Figure 1.5 : Influence of irradiation[12]

1.5.2 Influence of temperature

By varying the temperature from 25°C to 40°C, the characteristic (Ipv = (Vpv)) is provided in figures (1.5). It is noted that the temperature has a negligible influence on the value of the short-circuit current. However, the open-circuit voltage decreases significantly as the temperature increases, consequently reducing the extractable power. When designing an installation, the temperature variation at the site must be taken into account.[12]

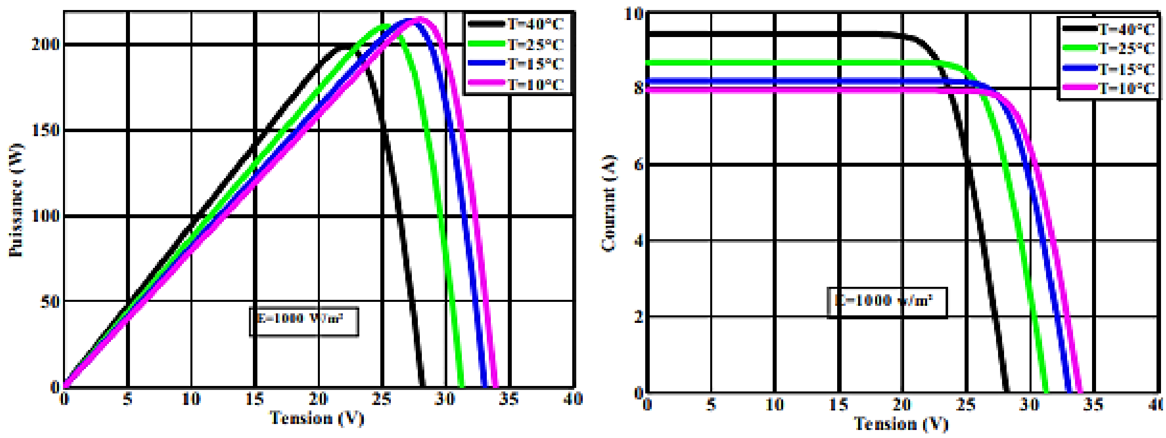


Figure1.6 .Influence of temperature [12]

1.6 components of photovoltaic system

1.6.1standalone systems

For standalone systems, the main components are:

- Photovoltaic panels (+ support structure)
- DC/DC charger/regulator
- Storage system (batteries, capacitors ...)
- Optionally, an inverter if the consumption is supplied with alternating current.
- Optionally, a backup generator.
- Optional: monitoring/supervision system for recording data and potentially accessing it remotely or via a web portal.

1.6.2 grid-connected photovoltaic systems

For grid-connected photovoltaic systems, the main components are:

- Photovoltaic panels (+ support structure)
- DC circuit breaker and protection enclosure
- Inverters
- AC circuit breaker and protection enclosure
- Optional: monitoring/supervision system for recording data and potentially accessing it remotely or via a web portal.[13]

1.7 Classification of photovoltaic systems

Photovoltaic systems can be categorized into two primary types:

1. Stand-alone PV systems
2. Grid-connected PV systems

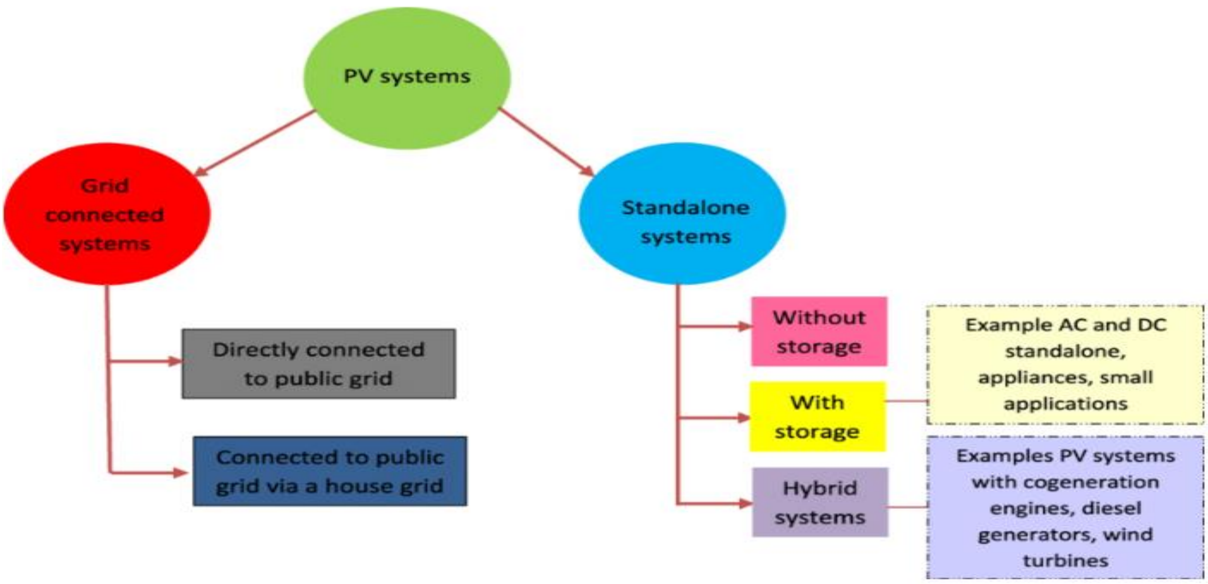


Figure 1.7.Classification of PV system

1.7.1 Stand-alone system

Stand-Alone PV refers to any system that exclusively relies on solar energy as its source of electrical power and can vary in scale from milliwatts to kilowatts or even larger capacities. These systems may incorporate batteries or accumulators to store the energy generated by the PV modules during daylight hours (sunshine phase) for use during nighttime or periods of insufficient solar radiation. Figure (1.7) illustrates a typical installation scheme for such systems. Additionally, Stand-Alone PV setups can fulfill the energy requirements of various applications without the need for batteries, such as residential PV installations.[14]

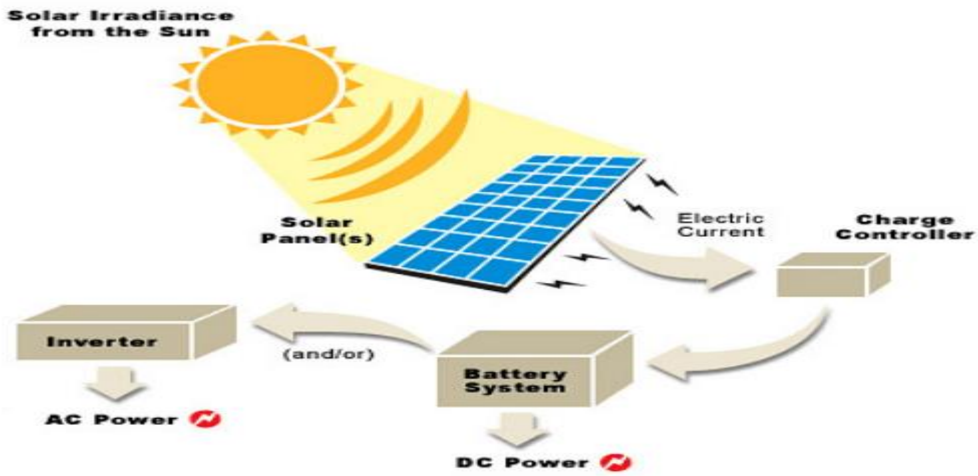


Figure 1.8: General schematic of a PV system [14]

1.7.2 Grid-connected photovoltaic System

Photovoltaic power systems connected to the grid, also known as grid-tied systems, are modern and innovative setups. They typically consist of an array of photovoltaic panels and an inverter capable of converting the energy generated by the panels. With these systems, electric power is supplied closer to the point of consumption, offering the advantage of enhancing transmission capacity and reducing the need for extensive distribution lines. Special precautions are necessary for injecting photovoltaic power into the grid, requiring inverters equipped with various protections to handle bidirectional electricity flow, as depicted in Figure (1.8).[14]

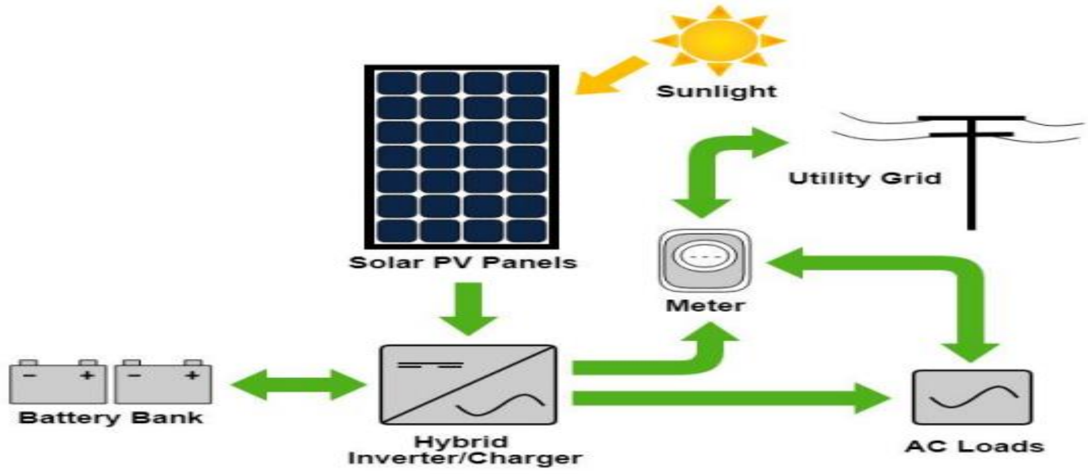


Figure1. 9. Diagram of a PV system connected to the grid, with batteries [14]

1.8 Quality and standards of grid-connected photovoltaic systems

The quality and standards of a grid-connected system encompass the following aspects[15]:

-Isolating photovoltaic systems from the grid during grid failure to prevent islanding issues.
-Reinforcing the stability and quality of power supplied to the grid through the reduction of harmonic pollution.
ˆ- Preventing adverse effects on grid segments, such as single-phase and three-phase imbalances.
- Enhancing grid stability by mitigating frequency fluctuations and voltage drops.

These measures are essential for ensuring the seamless and reliable integration of photovoltaic systems with the grid, thereby minimizing any potential adverse impacts on grid stability and power quality. Adherence to these standards facilitates a stable and harmonious operation between solar energy production and the electrical grid.

1.9 Advantages and disadvantages of photovoltaic systems

While photovoltaic systems present various benefits, they also come with certain drawbacks, which will be discussed in the following subsections [16 ,17]

1.9.1Advantages

1. **Sustainable Energy Source:** Photovoltaic systems harness solar energy, making them a sustainable energy source independent of fossil fuels.

2. **Cost-effectiveness:** Despite the potentially high initial cost, photovoltaic systems can prove highly cost-effective in the long run due to free energy production and minimal operating costs.

3. **Low Maintenance:** Photovoltaic systems require minimal maintenance and boast a long lifespan, enhancing their reliability as an energy source.

4. Safe and risk-free technology: Photovoltaic systems are considered safe because they do not involve any moving parts or combustible materials, reducing the risk of accidents such as fires or explosions. Additionally, they do not emit harmful pollutants or greenhouse gases during operation, contributing to a cleaner environment.

5.Clean, non-polluting energy: This means that photovoltaic systems do not release any pollutants into the atmosphere during operation, making them a clean and environmentally friendly source of energy. By harnessing solar energy, photovoltaic systems contribute to reducing air pollution, mitigating climate change, and preserving natural resources. Additionally, the production of electricity from sunlight is renewable and sustainable, as sunlight is an abundant and inexhaustible source of energy.

1.9.2disadvantages

1. The efficiency of PV cells remains relatively low: Photovoltaic cell efficiency refers to the percentage of sunlight that is converted into usable electrical energy. Although PV technology has improved over the years, with research focusing on increasing efficiency, the current efficiency levels are still not optimal.

2. The investment cost is relatively high: Investment cost refers to the total expenditure needed to purchase and install the necessary equipment for a photovoltaic system, including solar panels, inverters, mounting structures, wiring, and associated components. Additionally, costs may also include expenses related to labor, permits, and other administrative fees.

3. There is no electricity production in the evening and at night: Photovoltaic systems rely on solar panels to convert sunlight into electricity through the photovoltaic effect. When sunlight hits the solar panels, photons of light excite electrons in the semiconductor material of the panels, generating an electric current. However, this process requires direct sunlight, and electricity production significantly decreases or ceases altogether when there is insufficient sunlight, such as during the evening and at night.

4. Space requirements: Effective utilization of photovoltaic systems necessitates adequate space, posing challenges, particularly in densely populated urban areas.

5. Energy storage: Storing surplus energy can be complex and often involves additional expenses.

Conclusion:

This chapter provided a comprehensive overview of photovoltaic energy, elucidating the photovoltaic effect and the fundamental principle of photovoltaic conversion. It extensively discussed various types of photovoltaic cells, outlining their distinctive characteristics and the modeling techniques employed for their analysis. Furthermore, the chapter explored the concept of a photovoltaic generator, investigating the influence of irradiation and temperature on its operational performance. It also scrutinized the different constituents comprising a photovoltaic system. Finally, the chapter concluded with an examination of the classification of PV systems, underscoring their respective advantages and disadvantages. Looking ahead to the subsequent chapter, the narrative will pivot towards the regulation of converters in grid-connected photovoltaic systems.

Chapter2: Grid connected photovoltaic system converters control

Introduction

This chapter is dedicated to the control of converters in grid-connected photovoltaic systems. It starts by giving an overview of the configuration of grid-connected photovoltaic systems, the different types of systems, and the classification of the converters employed (DC-DC/DC-AC). Following this, the chapter delves into the structure, classification, and modeling of DC-DC converters and three-phase inverters. It elaborates on the principles and characteristics of Pulse Width Modulation (PWM) control, followed by an explanation of Maximum Power Point Tracking (MPPT) control, various MPPT methods, and their respective characteristics. The chapter wraps up by addressing the voltage source inverters (VSI) control and employing the Phase-Locked Loop (PLL) method for synchronization.

2.1 Grid-connected photovoltaic system

2.1.1 Definition

A grid-connected photovoltaic system, directly linked to the electrical grid, is comprised of multiple components collaborating to convert sunlight into electricity and supply it to the grid. Typically installed at sites connected to the grid (like those serviced by Sonelgaz in Algeria), such systems are commonly found in residential or commercial settings aiming to leverage renewable energy sources with ample sunlight. Unlike off-grid setups, grid-connected photovoltaic generators forego the need for energy storage, thereby circumventing the most challenging and expensive aspect of solar power implementation.[20]

2.2 Grid-connected PV system converters

As depicted in Figure (2.1), two primary converters are employed to adjust the extracted power from the photovoltaic module and convert it to fulfill the needs of the electrical grid. These converters include the DC/DC converter and the DC/AC converter.

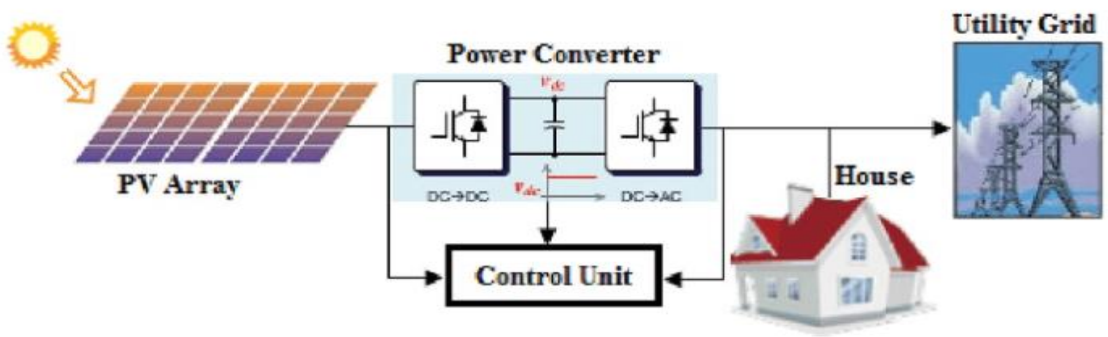


Figure2.1. Configuration of the grid-connected photovoltaic system

2.2.1 DC/DC converter

In numerous industrial settings, there's a need to transform a fixed-voltage DC source into a variable-voltage DC source. A DC-DC converter achieves this conversion directly from DC to DC and is commonly referred to simply as a DC converter. Analogous to an AC transformer, a DC converter operates with a continuously adjustable turns ratio. Much like a transformer, it enables both stepping down and stepping up of a DC voltage source.[21]

2.2.1.1 The three fundamental topologies of DC/DC converters are as follows:

1. Buck converter (step-down)
2. Boost converter (step-up)
3. Buck-boost converter (Step-down or step-up)

2.2.1.2 Buck converter

The buck converter circuit, shown in Figure 2.1, converts a higher DC input voltage into a lower DC output voltage. The basic configuration of a buck DC-DC converter includes a controlled switch (S), an uncontrolled switch (diode, D), an inductor (L), a capacitor (C), and a load resistance(R).[22]

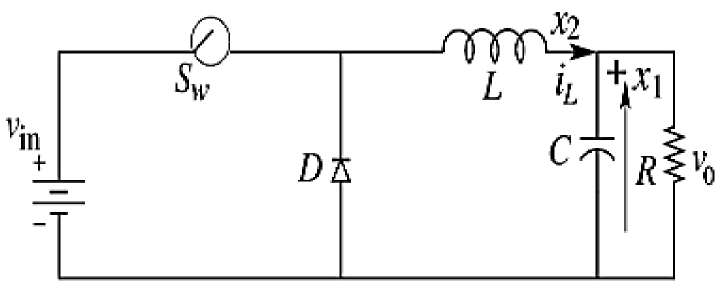


Figure2.2: DC-DC buck converter topology [22]

2.2.1.3 Boost converter

A boost converter, also known as a step-up converter, is a non-isolated DC/DC converter that is widely used, especially in uninterruptible power supplies (UPS) and photovoltaic (PV) systems. This is because charging a battery requires a high DC voltage to achieve a full charge. Figure 2.3 illustrates the basic structure of a boost converter. The theory behind a boost converter is relatively straightforward compared to other types of converters. When the switch

(S) is ON, the current flows exclusively through the inductor, storing energy in the process. When the switch (S) is OFF, the energy stored in the inductor is transferred to a capacitor, which typically has a large capacity to store a significant amount of energy. This energy is then converted to a high DC voltage for the load. [23]

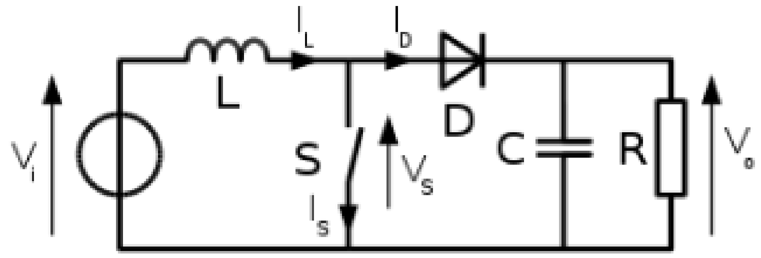


Figure 2.3: Boost converter circuit [24]

2.2.1.4 Buck boost converter

The key components in a buck-boost converter are similar to those in buck and boost converter types, but their arrangement differs. In Figure (2.4) of the buck-boost converter, the duty cycle can adjust to produce either step-up or step-down voltage. However, during operation, when the switch is ON, the inductor starts to charge, storing energy in the converter. Once the switch turns OFF, the circuit transitions to a state where both the inductor and capacitor are active simultaneously, resulting in the conversion of all stored energy in the inductor to the capacitor. The voltage is primarily controlled by the duty cycle. A larger duty cycle leads to higher voltage in the load, while a smaller duty cycle results in lower voltage in the load.[23]

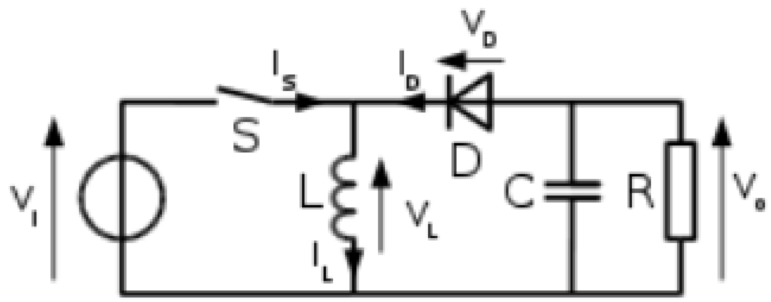


Figure2.4: Circuit converter buck boost [24]

2.2.1.5 Modeling of boost converter

The mathematical model that describes the boost converter connected to a photovoltaic generator can be expressed as follows [19]:

$$\begin{pmatrix} V_m \\ I_{dc} \end{pmatrix} = m.\begin{pmatrix} V_{DC} \\ I_l \end{pmatrix} \quad (2.1)$$

$$\frac{dV_{pv}}{dt} = \frac{1}{C}\ (I_l - I_{pv}) \quad (2.2)$$

$$\frac{dI_l}{dt} = \frac{I}{I_{pv}}\left(V_m - V_{pv}\right) - \frac{R_{pv}}{L_{pv}} I_l \quad (2.3)$$

. **Where:**

V_m = the modulated voltage;

I_{dc} = output current;

Il= the inductor current;

Vpv = photovoltaic voltage;

C_{pv} = photovoltaic capacitance;

I_{pv} = photovoltaic current;

R_{pv} = photovoltaic resistance;

L_{pv} = photovoltaic inductor.

2.2.2 DC/AC CONVERTER (Inverter)

2.2.2.1 Definition

DC/AC inverter circuits belong to the category of power electronics converters utilized for transforming DC voltage into a sinusoidal AC voltage waveform. This waveform's amplitude, frequency, and phase can be controlled to match the requirements of various user loads applications. They are extensively employed in industrial and commercial settings, such as adjustable speed drives (ASD) for AC motors, renewable energy conversion systems, and uninterruptible power supplies (UPS). In low-power scenarios, it's imperative for inverters to operate continuously without any interruptions.[25]

2.2.2.2 Classification of inverters

An inverter is a static converter that ensures the conversion from direct current to alternating current, powered by direct current. It periodically modifies the connections between the input and output, allowing for alternating current at the output.

A primary classification can be made by distinguishing between non-autonomous inverters and autonomous inverters. The autonomous inverter essentially depends on the nature of the generator and the load to which it is connected, leading to the distinction between voltage inverters and current inverters. A voltage inverter is a converter that is powered by a direct voltage source. This voltage 'U' is not affected by variations in the current 'i' passing through it. The voltage inverter is divided into two types: single-phase inverter Figure (2.5) and three-phase inverter Figure (2.6). [38]

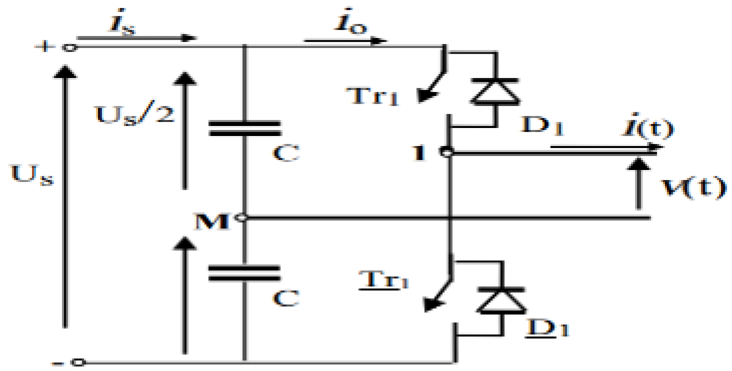


Figure2.5. Half-Bridge inverter

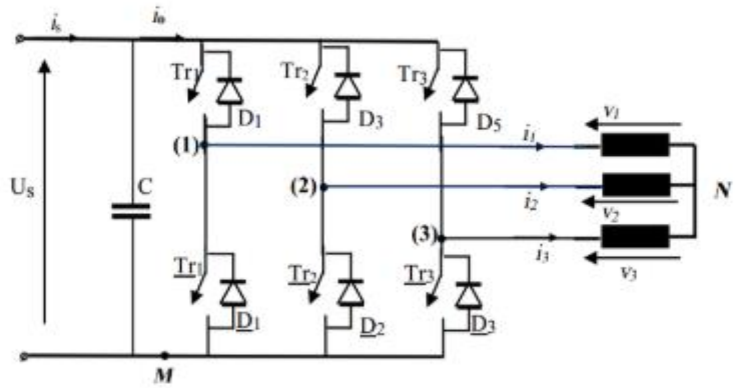


Figure2.6. Three-phase bridge inverter structure

2.2.2.3 Number of load phases

1. Single-Phase Inverters: These inverters generate a single-phase AC output waveform. They find frequent application in residential and small-scale commercial settings with relatively low

electrical loads. Typically, single-phase inverters are utilized in systems connected to single-phase AC power supply grids.

2. Three-Phase Inverters: Three-phase inverters produce a three-phase AC output waveform. They are commonly utilized in larger-scale commercial and industrial environments where the electrical load is higher.[19]

2.2.2.4 Nature of the source

1. Current Inverter:

A Current Source Inverter (CSI) is a variant of DC-AC Inverter that transforms DC input current into AC current at a specified frequency. The frequency of the resulting AC current is determined by the operating frequency of the switching components, such as thyristors, transistors, and so forth.[26]

2. Voltage Inverter:

A voltage inverter, also known as a voltage source inverter (VSI), is an inverter that regulates the output voltage while allowing the current to vary. It converts a fixed DC voltage source into an AC voltage waveform. Voltage inverters are widely used in various applications, including grid-tied solar inverters, uninterruptible power supplies (UPS), and adjustable speed drives, where controlling the voltage is crucial.[19]

2.2.2.5 Control mode

1. Full wave control: Full wave control involves operating the inverter by switching semiconductor devices (such as transistors or thyristors) in a pattern that rectifies both the positive and negative half-cycles of the output waveform. This enables precise regulation of both the output voltage and frequency, albeit at the expense of requiring more complex circuitry and control algorithms.[27]

2. Synchronous control: Synchronous control, alternatively termed synchronous rectification, is a control method that synchronizes the operation of the inverter's semiconductor devices with either the input voltage or the output waveform. By aligning the switching actions with the waveform, the inverter reduces power losses and enhances overall efficiency. Synchronous control finds widespread application in high-power scenarios where efficiency plays a pivotal role.

3. Pulse Width Modulation (PWM) control: As commonly understood, a PWM signal remains in an "ON" state for a specific duration and then switches to an "OFF" state for another period.

The proportion of time during which the signal is "ON" is termed as the duty cycle. If the signal remains consistently "ON," its duty cycle reaches 100%. The duty cycle is calculated using the following formula:

$$Duty\ cucle = \frac{Turnontime}{Turn\ on\ time + Turn\ of\ time} \tag{2.4}$$

The mean voltage is contingent upon the duty cycle. Consequently, altering the width of the "ON" duration within a pulse enables modulation of the average voltage value.[28]

2.3 Three phase inverter structure

The three-phase voltage inverter is immediately derived from three single-phase half-bridges. The three-phase inverter with six switches is obtained. Each half-bridge comprises a thyristor (or transistor) and a diode. The DC voltage source is obtained from a rectifier bridge. To ensure continuity of the output

alternating currents I_{fa}, I_{fb}, I_{fc}, switches S_1, S_4, S_2, S_5, S_3, and S_6 must complement each other pairwise.[29]

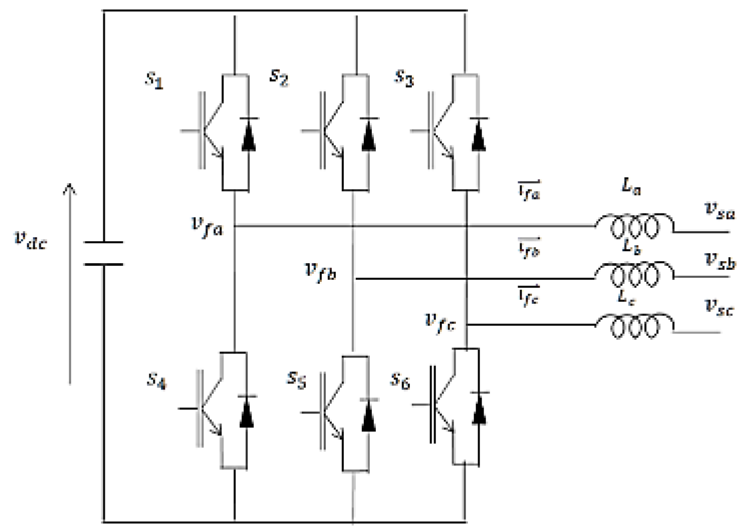


Figure2.7. Block diagram of the three-phase inverter[19]

2.3.1 Modeling of three-phase inverter

$$V_{An} = \frac{1}{3}(V_{AB} - V_{CA}) \tag{2.5}$$

$$V_{Bn} = \frac{1}{3}(V_{BC} - V_{AB}) \tag{2.6}$$

$$V_{Cn} = \frac{1}{3}(V_{CAB} - V_{CCB}) \tag{2.7}$$

Where VAO, VBO, and VCO are the phase voltages of the load.

Representing the point "o", the voltages between phases can also be expressed as follows:

$$V_{AB} = (V_{AO} - V_{BO}) \tag{2.8}$$

$$V_{BC} = (V_{BO} - V_{CO}) \tag{2.9}$$

$$V_{AB} = (V_{CO} - V_{AO}) \tag{2.10}$$

Where:

V_{no} represents the neutral voltage of the load.

By substituting equations (2.5), (2.6), and (2.7) into equations (2.8), (2.9), and (2.10), we obtain the following expression.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{AO} \\ V_{BO} \\ V_{CO} \end{bmatrix} \tag{2.11}$$

Using the given relationship:

$$V_{AO} = (V_A - V_{nO}) \tag{2.12}$$

$$V_{BO} = (V_B - V_{nO}) \tag{2.13}$$

$$V_{CO} = (V_C - V_{nO}) \tag{2.14}$$

Equation (2.8) depicts the mathematical model of the three-phase inverter utilizing Pulse Width Modulation (PWM) technique.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{U_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{2.15}$$

Where:

Udc = dc voltage,

S1, S2, S3 = the state of the switches.

2.4 Pulse width modulation control (PWM control)

2.4.1 Principle of PWM

Pulse width modulation (PWM) is a modulation technique that generates variable-width pulses to represent the amplitude of an analog input signal. The output switching transistor is on more of the time for a high-amplitude signal and off more of the time for a low-amplitude signal.[30]

2.4.2 Characterize the command

The PWM technique is characterized by:

1. The adjustment coefficient: The modulation adjustment coefficient, represented as (V_{Rm}), is defined as the ratio between the amplitude of the reference voltage modulation (V_{pm})and the peak value of the carrier signal (V_{pm}).[31.19]

$$r = \frac{V_{Rm}}{V_{pm}} \tag{2.16}$$

2. Modulation index: The modulation index (m) is defined as the ratio of the modulation frequency to the reference frequency.[19]

$$m = \frac{f_p}{f_r} \tag{2.17}$$

Where

Fp = carrier frequency.

2.4.3 Modeling of pulse width modulation

Modeling the Sinusoidal Pulse Width Modulation (PWM) command can be expressed through the following equations:

Reference equation: The three sinusoidal reference voltages are provided by

$$\begin{bmatrix} V_{Aref} = V_{rm} sin2\Pi \ f_r t \\ V_{Bref} = V_{rm} sin2\Pi \ f_r t \\ V_{Cref} = V_{rm} sin2\Pi \ f_r t \end{bmatrix} \quad (2.18)$$

Carrier equation: The triangular carrier equation is expressed by:

$$V_p(t) = V_{mp}\left[\frac{1}{2} - \frac{\sin\left(\cos\left(2pF_p(t)\right)\right)}{pi}\right] \quad (2.19)$$

The diagram depicted in Figure (2.6) illustrates a timing diagram produced by a three-phase sine-triangle PWM command.

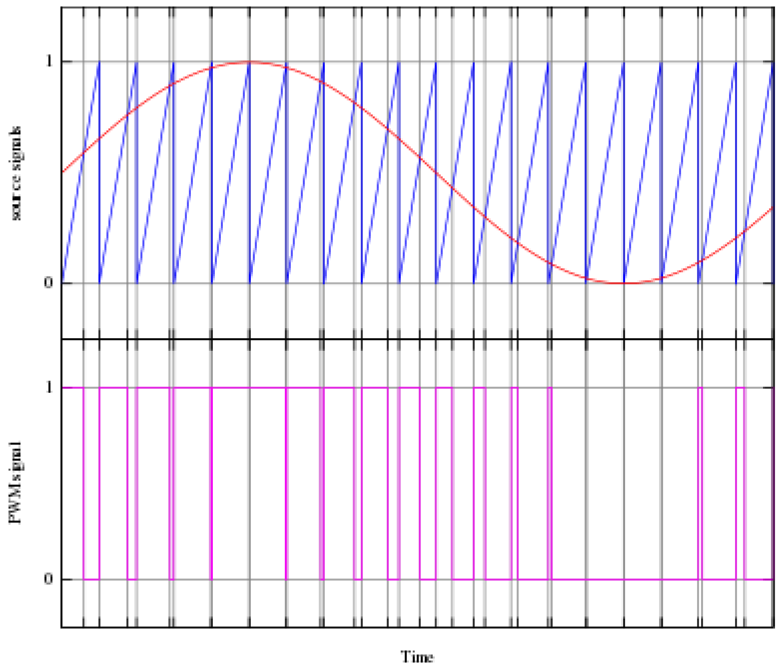


Figure2.8. Diagram delivered by an PWM command

2.5 Maximum POWER POINT Tracking (MPPT)

2.5.1 Principle

A MPPT, from English "Maximum Power Point Tracking," is a principle that allows tracking, as its name suggests, the maximum power point of a nonlinear electrical generator.

Consequently, for the same illumination, the delivered power will be different depending on the load. A MPPT controller thus allows controlling the static converter connecting the load (such as a battery) and the photovoltaic panel in such a way as to constantly supply the maximum power to the load at each moment. [32]

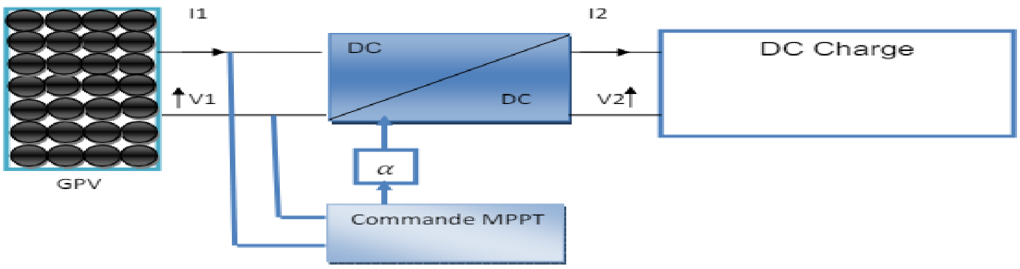


Figure2.9. Diagram delivered by an PWM command [32]

2.5.1.1 Direct methods

Direct determination methods of MPPT depend on the general operating characteristics and employ measurements of current and voltage. Of these techniques, the most prevalent one is the "Perturb and Observe" method. This approach entails adjusting the duty cycle to modify the operating point of the solar power generator.[19]

2.6 MPPT techniques

Several techniques are used to track the maximum power point (MPP). Among the most commonly employed techniques are:

- Perturb and Observe
- Incremental Conductance
- Fractional open circuit voltage
- Fractional short circuit current
- Fuzzy Logic Control

2.6.1 Perturb and Observe

The "Perturb & Observe" (P & O) method provides a straightforward approach to maximum power point tracking. It utilizes a single sensor, typically a voltage sensor, to measure the voltage of the solar cell array, leading to reduced implementation costs and simplified implementation. The time complexity of the P & O algorithm is generally low. However, as it approaches the maximum power point (MPP), it may experience overshooting and continue to perturb in both directions. To mitigate this issue, an appropriate error limit can be defined or a waiting function can be incorporated to increase the algorithm's time complexity. These adjustments help ensure that the algorithm operates within the vicinity of the MPP. [33]

2.6.2 Incremental Conductance

This technique is based on understanding the variation in the conductance of the PV module and its implications for the position of the operating point relative to a Maximum Power Point (MPP). Thus, the conductance of the photovoltaic module is defined by the ratio of the current to the voltage of the PV module.[34]

2.6.3 Fractional open circuit voltage

Analysis of solar panel characteristics under varying insolation, temperature, and partial shading conditions reveals that the maximum power point voltage typically ranges between 0.6 to 0.8 times the open circuit voltage of the solar panel. The Fractional Open Circuit Voltage (FOCV) based tracking algorithm utilizes this information to conduct maximum power point tracking. By employing power converter modules, the input voltage of the converter, equivalent to the solar panel terminal voltage, is maintained at 0.7 times its open circuit voltage. Real-time changes in temperature, sunlight intensity, and shading can lead to variations in the open circuit voltage. Consequently, the conventional FOCV-based maximum power point tracking algorithm becomes less effective as environmental factors significantly impact the solar panel characteristics. However, under stable temperature, consistent insolation conditions, and shade-free environments, the conventional FOCV method operates flawlessly.[35]

2.6.4 Fractional short circuit current

The Fractional Short Circuit Current (FSCC) technique is a direct and effective approach for maximizing the power output of a photovoltaic system. In this method, the maximum power point is tracked by determining the short circuit current (Isc) of the PV array after temporarily disconnecting it. FSCC can be implemented using analog or digital methods. The underlying principle of this technique is based on the close proximity between the short circuit current (Isc) and the current at the maximum power point (Impp). Leveraging this relationship enables the FSCC technique to achieve precise and rapid MPPT.[19]

2.6.5 Fuzzy Logic Control

Fuzzy logic-based control (referred to as Fuzzy Logic Control in Anglo-Saxon literature) is becoming increasingly popular due to the evolution of microcontrollers [39-40]. The advantage of this technique is its ability to operate with imprecise input values and its lack of need for a highly accurate mathematical model. Additionally, it can handle nonlinearities. The principle of fuzzy control is based on two input variables, which are the error E and the change in error ΔE, and one output variable Δα (variation of the duty cycle). The value of the output variable, which controls the static converter to search for the MPP, is determined using a truth table and the evolution of input parameters.[36]

2.7 Characteristics of different MPPT techniques

The characteristic of different mppt techniques are given in the following table (2.1) [39]:

MPPT technique	Convergence speed	Implementation complexity	Periodic tuning	Sensed parameters
Perturb and observe	Varies	Low	No	Voltage
Incremental Conductance	Varies	Medium	No	Voltage, current
Fractional Voc	Medium	Low	Yes	Voltage
Fractional Isc	Medium	Medium	Yes	current
Fuzzy logic control	Fast	High	Yes	Varies

Table 2.1: Characteristics of different MPPT technique

2.8 Perturb & Observe Algorithm(P&O)

The Perturb and Observe (P&O) method is generally the most widely used due to its simplicity and ease of implementation. This algorithm takes the voltage Vpv and current Ipv values as inputs, and outputs the duty cycle value α. The principle of this algorithm (as its name suggests and as shown in Figure (2.8) is to perturb the voltage Vpv while controlling the duty cycle α. After this perturbation, the power supplied by the panel P(k) is calculated and compared to the previous value P(k-1). If the power increases, we are approaching the Maximum Power Point (MPP), and the variation of the duty cycle is maintained in the same direction. Conversely, if the power decreases, we are moving away from the MPP. Then, the direction of the duty cycle variation must be reversed. This is illustrated in Figure(2.8). [37]

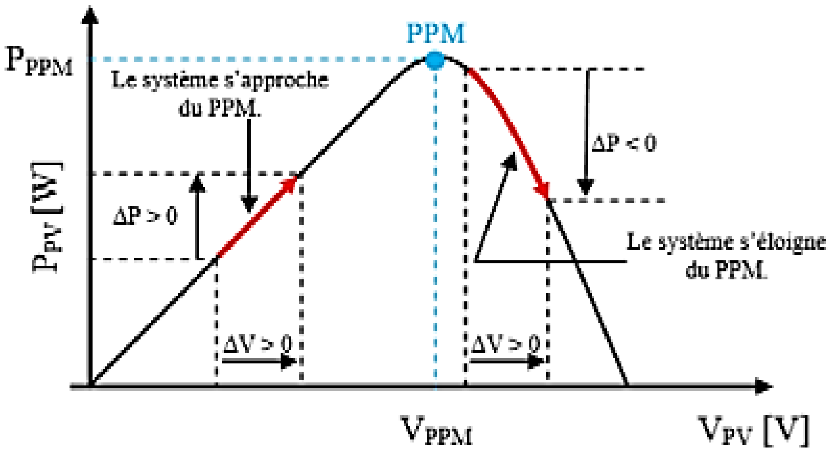


Figure2.10:Principle of P&O method[37]

Due to its ease of implementation, the Perturb & Observe (P&O) method is frequently used despite the oscillation issues around the MPP because the search must be periodically repeated to force the system to oscillate around the MPP. Moreover, for sudden variations in weather conditions and/or load, this method sometimes presents errors in interpretation regarding the direction to follow to reach the MPP. [37]

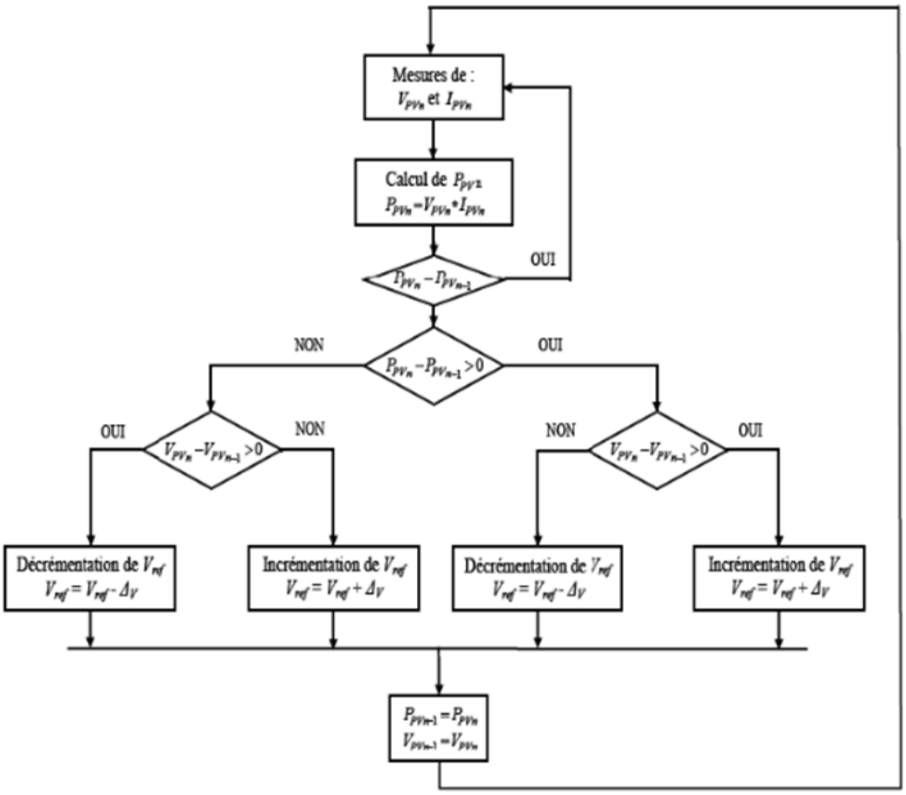


Figure2.11: Flowchart of the Perturb and Observe algorithm [37]

2.9. The control section of the proposed structure focuses on the inverter-grid interface

2.9.1 Voltage source inverter (VSI)

A Voltage Source Inverter (VSI) is a device that changes a one-way voltage pattern into a two-way voltage pattern. It acts as a converter, altering the voltage from direct current (DC) to alternating current (AC). In an ideal scenario, a Voltage Source Inverter maintains a steady voltage throughout the conversion process. The typical model for current control in the inner control loop is as follows:

$$I_d = \left(K_p + \frac{K_i}{S}\right)\left(P_{ref} - P_{cal}\right) \quad (2.20)$$

$$I_q = \left(K_p + \frac{K_i}{S}\right)\left(Q_{ref} - Q_{cal}\right) \quad (2.21)$$

The typical model for voltage control in the outer control loop is as follows:

$$U_d = \left(K_p + \frac{K_i}{s}\right)\left(I_{dref} - P_{dcal}\right) \tag{2.22}$$

$$U_q = \left(K_p + \frac{K_i}{s}\right)\left(I_{qref} - I_{qcal}\right) \tag{2.23}$$

2.9.2 Active & reactive power control (P & Q)

The aim of this control type is to regulate both the active and reactive power injected into the grid. The control circuit is tasked with adjusting the currents to ensure that the output current from the inverter is smooth and synchronized with the respective phase-to-neutral voltage. The detailed schematic diagram provided below depicts this control, and its principle is explained in the following figure.

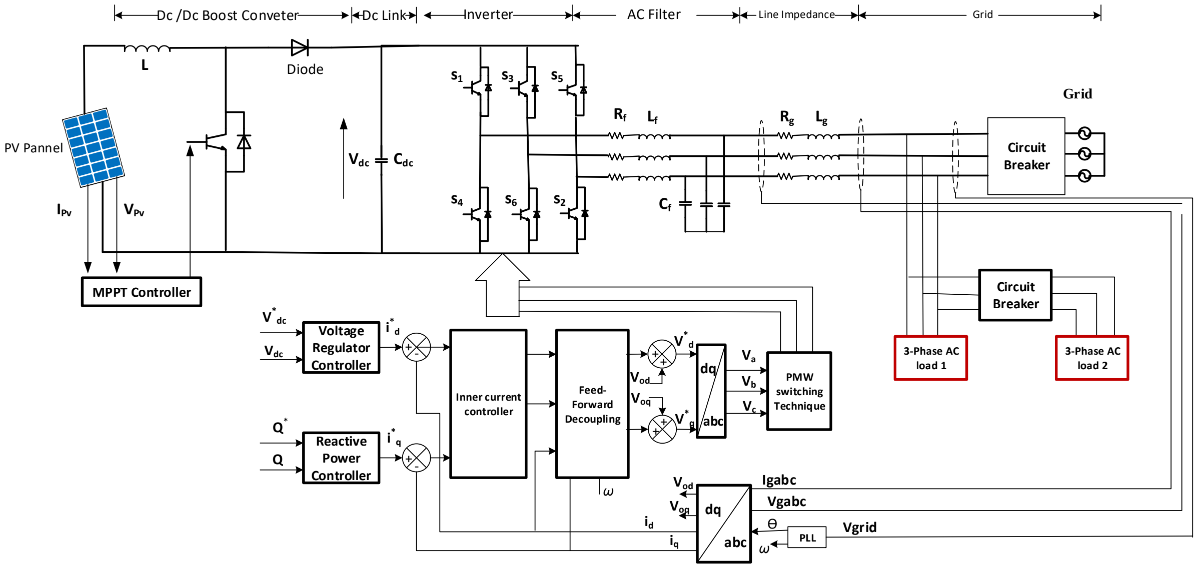


Figure.2.12. Active & reactive power control (P & Q)

The system analysis and subsequent simplifications have led to the conclusion that the reference currents generated by the upstream control will be injected at the photovoltaic (PV) production connection point. These currents are calculated using power references and voltage measurements taken at the connection point. Afterwards, they undergo Park transformation according to the following equations:

$$P_{ref} = \left(V_{dr}I_{dref} + V_{qr}I_{qref}\right) \tag{2. 24}$$

$$Q_{ref} = \left(V_{dr}I_{dref} + V_{qr}I_{qref}\right) \tag{2. 25}$$

$$I_{dref} = \frac{\left(V_{dr}P_{ref}+V_{qr}Q_{ref}\right)}{\left(V_{qr}+V_{qr}\right)^2} \quad (2.\ 26)$$

$$I_{qref} = \frac{\left(V_{dr}P_{ref}+V_{qr}Q_{ref}\right)}{\left(V_{qr}+V_{qr}\right)^2} \quad (2.27)$$

Where:

P_{ref} and Q_{ref} represent the reference powers of the PV production.

V_{dr} and V_{qr} represent the direct and quadrature components of the voltage, measured at the point of connection of PV production, in the Park transformation.

$I_{d\text{-}ref}$ and $I_{q\text{-}ref}$ are the reference direct and quadrature components of the current produced by the PV production and injected into the connected network.

To compute the currents, the measured voltage undergoes conversion to the Park reference system. Employing a Phase-Locked Loop (PLL) synchronizes the Park transformation with the measured voltage pulse on the network.

2.9.3 Control of the DC bus voltage

Managing the DC bus is a crucial procedure within the system. Observing voltage fluctuations at the capacitor terminals offers valuable understanding into the energy transfer dynamics between the capacitors and the network. Integrating the capacitive current allows us to derive the temporal evolution of the terminal voltage.

By controlling the power transmitted through the system, it becomes feasible to manage the energy stored in the capacitor and thus regulate the voltage of the DC bus. The control loop established for this objective is illustrated in Figure (2.11) below.[19]

$$I_C = I_{pv} - I_{ond} \quad (2.28)$$

and

$$V_{dc} = \frac{1}{C}\int\left(I_{pv} - I_{ond}\right)dt \quad (2.29)$$

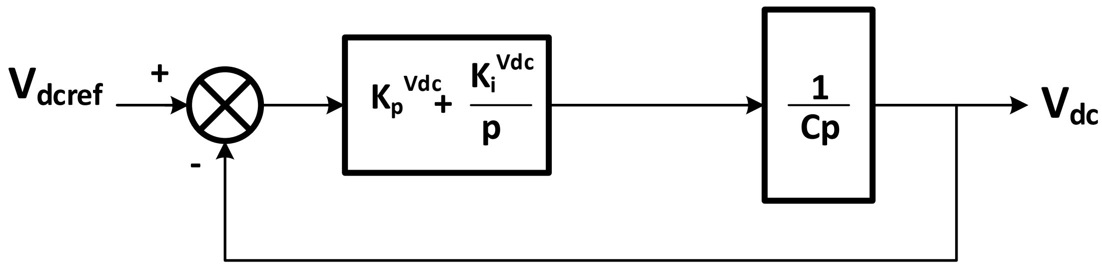


Figure2.13. Diagram DC bus voltage regulation loop [19]

2.10 Phase locked loop (PLL)

The Phase-Locked Loop (PLL) is a widely used integrated circuit in electronics. It is a phase or frequency servo system that controls the frequency of a voltage-controlled oscillator (VCO) to an input signal:

• The core of the PLL is the VCO, which provides an output sinusoidal or square wave signal with an instantaneous frequency fs(t) dependent on v(t).

• The phase comparator develops a voltage u(t) depending on the phase difference between the input and output signals.

• The low-pass filter smooths this voltage u(t) by maintaining its average value and removing harmonics.

• V_c: control voltage.

• φ_e: input phase.

• φ_s: output phase

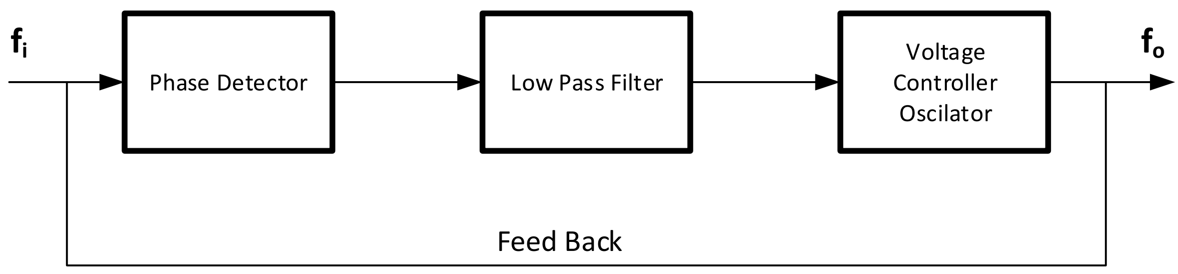


Figure 2.14: Block diagram PLL [19]

2.10.1 Phase detector

This is an analog multiplier. It is a circuit with two inputs that provides an output voltage proportional to the phase difference of the signals at its input, with its output providing a voltage:

$$V(t) = k(\varphi_e \varphi_s) \qquad (2.30)$$

Given that:

K: A constant called, whose dimension is expressed in volt/radian.

φ_e: Input phase of the phase comparator.

φ_s: Output phase of the phase comparator.

2.10.1.1 Low Pass Filter

Its existence is essential because it allows, through the choice of its parameters, to achieve a stable control system. Its role is to only allow signals of low frequencies, lower than a certain well-defined frequency, called the cutoff frequency, to pass through.

2.10.1.2 Voltage controlled oscillator

Its role is to deliver a periodic signal, whose frequency depends on the control voltage applied to its input.

2.10.2 Synchronization

The concept behind the Park PLL is depicted in this diagram. In this PLL, the phase angle is detected by aligning the rotating reference frame of the PLL with the utility voltage vector. Setting the reference voltage Vrd* to zero along the direct axis enables the PLL to lock onto the phase angle of the utility voltage vector. The output of the PI controller represents the inverter output frequency, which is then integrated to determine the inverter phase angle θ. Additionally, the instantaneous frequency and amplitude of the voltage vector are also calculated. When the difference between the grid phase angle θr and the inverter phase angle θond approaches zero (δ θ = θ), the PLL becomes active.

The parameters of the PI controller are determined using the equivalent linear models depicted in Figure (2.13). These models characterize the system dynamics and serve as the foundation for controller design [19].

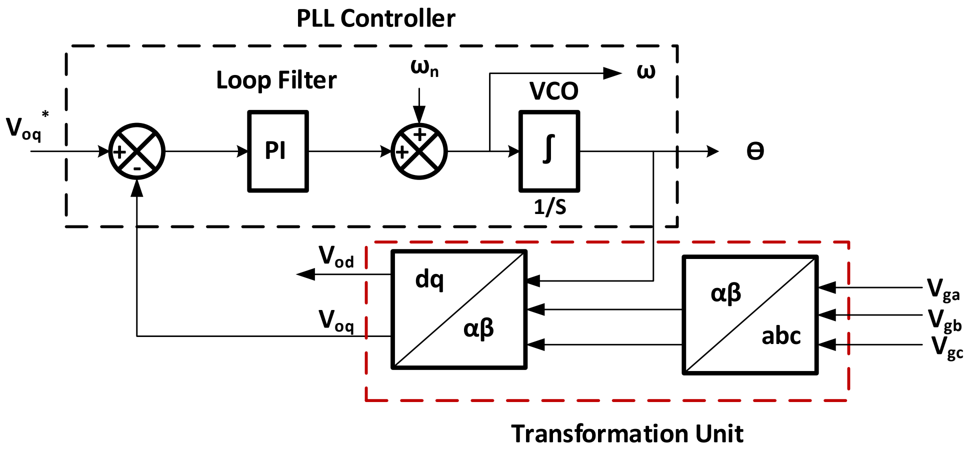


Figure2.15: Structure of a PLL system for grid synchronization [40]

Conclusion

In the preceding two chapters, we investigated into the control aspects of a grid-connected photovoltaic system converter. Initially, we introduced the grid-connected photovoltaic generation system and explained the DC/DC converter. Subsequently, we investigated into the structure and variants of chopper circuits, followed by an exploration of the operational principle and modeling of the boost converter. Furthermore, we outlined and categorized the DC/AC converter, and elaborated on the structure and modeling of the three-phase inverter. Our discussion extended to the principle and attributes of pulse width modulation (PWM), alongside an examination of various techniques for maximum power point tracking (MPPT). A detailed explanation was provided for the Perturb & Observe algorithm, encompassing its principle and methodology. Conclusively, we probed into the control mechanism of the Voltage Source Inverter (VSI) and the synchronization utilizing the phase-locked loop (PLL) In the approaching chapter, our focus will shift towards simulation and the resultant outcomes of the system.

Chapter3: Simulation and implementation of the proposed Grid-connected PV system

Introduction

This chapter is dedicated to simulating and presenting the results of the proposed grid-connected PV system. The simulation is conducted using the PSIM platform, enabling us to model various components of the system, such as the PV generator, the boost converter. The outcomes from each component will be separately presented and discussed. Additionally, the entire system will be simulated, and the corresponding results will be comprehensively presented and analyzed Subsequently, the system will be connected to LAUNCHXL-F28379D and simulated externally.

3.1 Proposed photovoltaic system

The proposed grid-connected PV system depicted in Figure (3.1) consists of several key components. Initially, there's a photovoltaic generator linked to a boost converter, tasked with tracking the maximum power point. Following this, a voltage source inverter (VSI) is integrated, connecting to the DC bus (which is the output of the boost converter) on one end, and to the point of common coupling via an L filter on the other. The VSI's control mechanism maintains a consistent DC bus voltage, ensuring stability in its output voltage. Synchronization between the VSI output voltage and the utility grid is accomplished through a phase-locked loop (PLL) control strategy, ensuring precise alignment and synchronization with the utility grid voltage.

3.2 Characteristics of the used PV panel

Prior to commencing the simulation of the proposed system's components, it's essential to present an overview of the characteristics of the PV panel used to form the PV generator. The table presented below outlines both the physical and electrical attributes of the utilized PV panel under Standard Test Conditions (STC) (G=1000 W/m^2, 25°C).

In order to graph the I-V and P-V characteristics of the utilized PV panel, its output is linked to a capacitor C. Following this, the current passing through the capacitor (I_{pv}) and the voltage across the capacitor (V_{pv}) are gauged and then multiplied to derive the panel power (Ppv), as depicted in Figure (3.2).

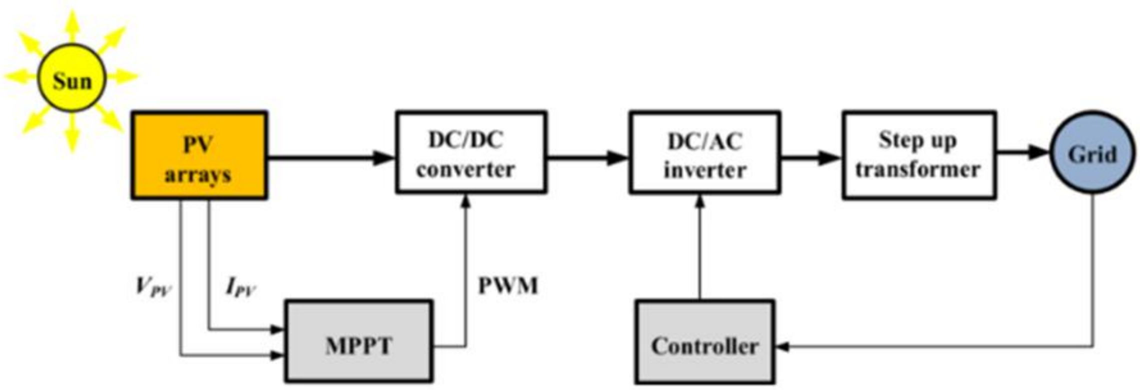


Figure 3.1. Schematic diagram of a photovoltaic system connected to the grid

Electrical characteristic	value
Number of panels in series (Ns)	8
Number of panels in parallel (Np)	3
Short circuit current (I_{sc})	26.31
Open circuit voltage (V_{co})	357
Maximum power (P_{max})	7600
Maximum power voltage (V_{mp})	310
Maximum power current (I_{mp})	24.48

Table 3.1. Physical and electrical characteristics of the panel.

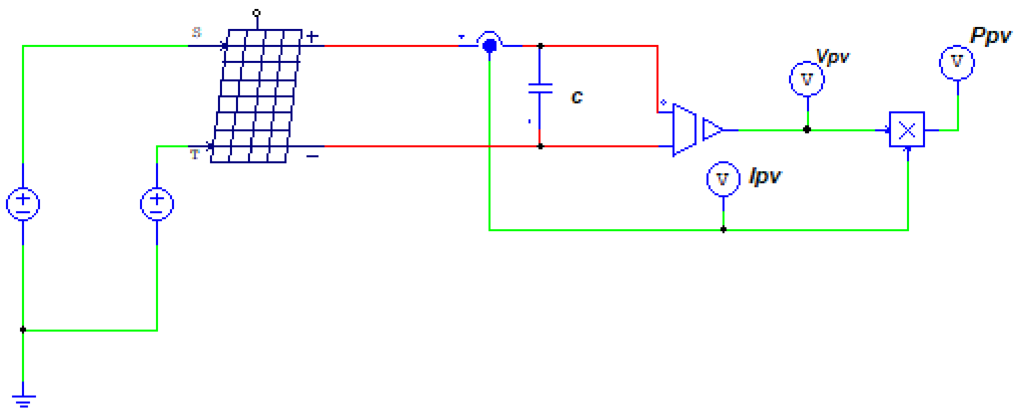


Figure 3.2. I-V and P-V plotting characteristic circuit of the PV panel.

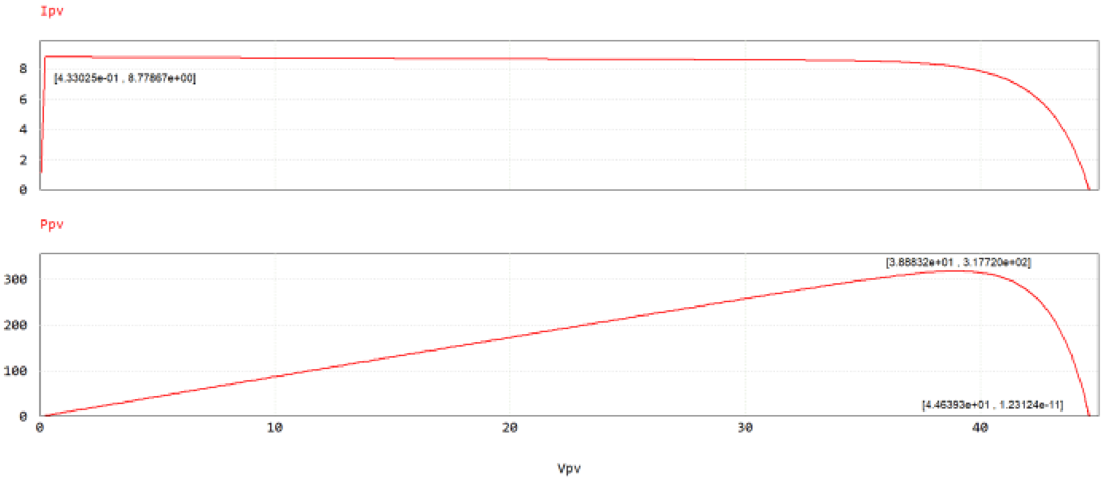


Figure 3.3. I-V and P-V characteristics of the panel

The I-V and P-V curves of the previous PV panel are presented in Figure (3.2), which clearly shows that the electrical characteristics are identical to those given in the table (3.1)

3.3 Characteristics of the used PV generator

Due to the low power generation of the individual PV panel, a PV generator was created by combining multiple panels in parallel or series configurations. However, the PSIM platform lacks the capability to design a PV generator solely by specifying the number of panels in parallel or series, and instead requires physical connections between them. This increases computation time and slows down simulation execution. Therefore, we opted to develop our PV generator based on the characteristics of the individual panel, while allowing for the specification of the number of panels in parallel or series only, as depicted in the figure below. The table summarizes the characteristics of the PV generator used. The same methodology used for the PV panel is applied to plot the I-V and P-V curves of the PV generator.

Elecrical characteristic	value
Number of panels in series (Ns)	8
Number of panel in parallel (Np)	3
Short circuit current (Isc)	26.31
Open circuit voltage (Vco)	357
Maximum power (Pmax)	7600
Maximum power voltage (Vmp)	310.3
Maximum power current (Imp)	24.48

Table 3.2: Physical and electrical characteristics of the PV generator

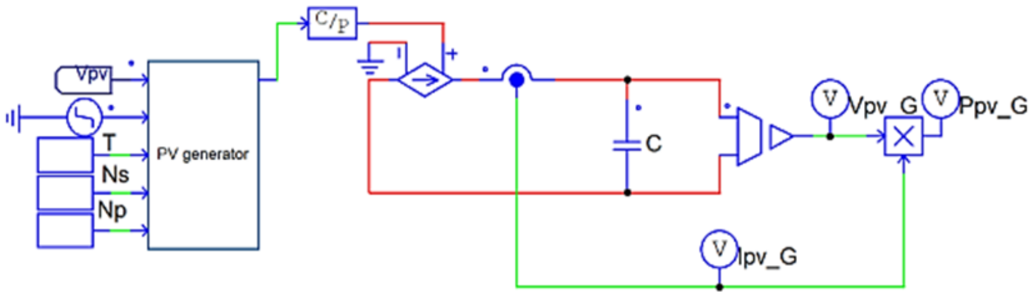


Figure 3.4: I-V and P-V plotting characteristic circuit of the PV generator.

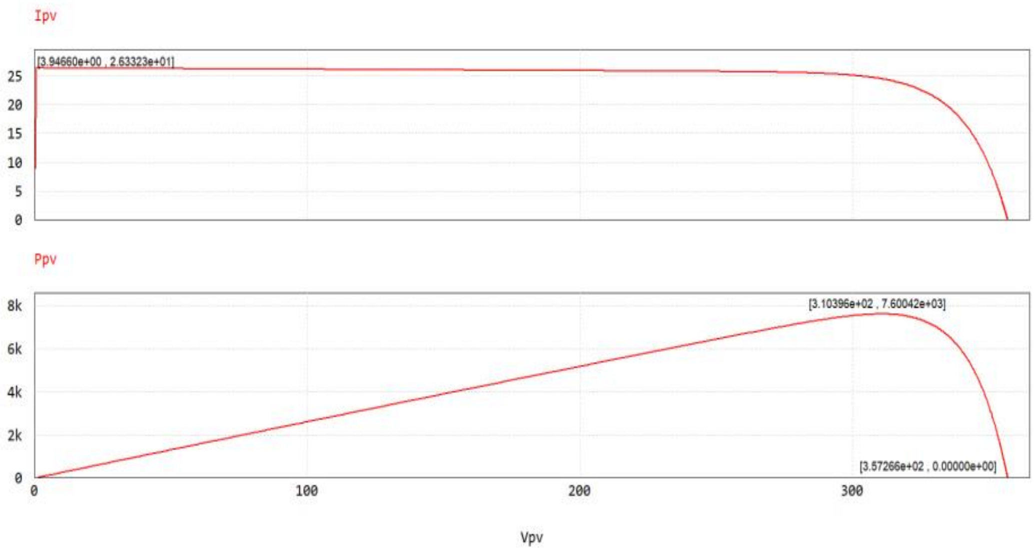


Figure 3.5. I-V and P-V characteristics of the PV generator under 100W/m^2, 25°

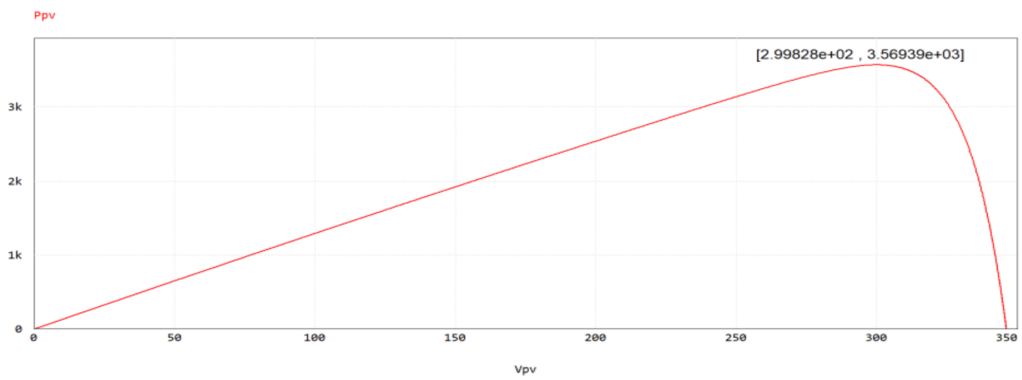


Figure 3.6. P-V Characteristic of the PV generator under 500W/m2, 25°

3.4 Boost converter

Before proceeding with the simulation, the first step involves determining the parameters of the boost converter. Unlike the classical converter, where its input is typically fixed, the sizing of this converter, used to track the maximum power point, differs. In this study, the boost converter comprises an input capacitor CI, an inductor L, and an output capacitor CO. The values of these three parameters are calculated using the following three equations: Inductor (L):

$$L = \frac{V_{mp} D_{mp}}{2dIF_s} \quad (3.1)$$

Where

V_{mp} = the maximum power voltage,

D_{mp} = D of maximum power,

dI= the current ripple

F_s = the switching frequency;

Input capacity (C-I):

$$C_I = \frac{4V_{mp} D_{mp}}{dV_I R_I F_s} \quad (3.2)$$

Where

R_I = input resistance,

dV_I= ripple voltage.

Output capacity (C-o):

$$C_o = \frac{2V_o D_{mp}}{dV_{V_o} R_o F_s} \quad (3.3)$$

Where

V0 = output voltage,

dV-0 = ripple voltage,

R0 = output resistance.

parameters	Value
Input inductance (L)	3mH
Input capacity (C-I)	3µF
Output capacity (C-o)	250µF
Load resistance (R)	100 omh

Table 3.3. Parameters of the boost converters

3.5 PV generator maximum power point tracking

Maximum Power Point Tracking (MPPT) algorithms are employed to ascertain the optimum output efficiency of a photovoltaic system. Ensuring that the PV array consistently operates in close proximity to this MPP offers the potential for achieving peak efficiency. To uphold the performance of our PV generator at its highest potential, it is linked to the boost converter, whose dimensions have been determined in preceding sections. The boost converter assumes a pivotal role in tracking the MPP through the utilization of the previously elucidated Perturb and Observe (P&O) algorithm. Figure (3.6) furnishes an intricate portrayal of the initial segment of the system, wherein the P&O algorithm has been integrated within a PSIM C block.

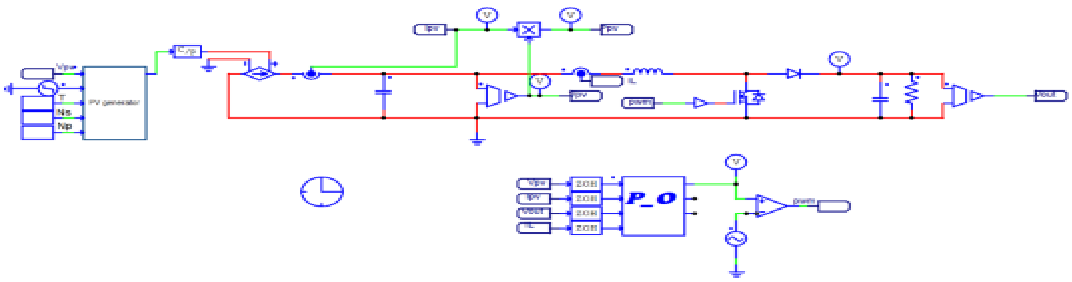


Figure 3.7. PV generator with boost converter controlled by P&O algorithm

Observing Figure (3.8), it's noticeable that at the 2.5s mark, the irradiance shifts from 1000 to 500 W/m2. Referring to Figure (3.5) and Figure (3.6), the MPPT points for these corresponding irradiance levels are determined to be 7.6 kW and 3.57 kW. The output power of the PV generator is measured at 7.58 kW and 3.565 kW, confirming the achievement of MPP for both irradiations with a negligible error of 0.003% and 0.001% respectively. This outcome underscores the effectiveness of the MPPT control in accurately tracking and maintaining the PV system at the maximum power point. These findings affirm the high efficiency of the circuit sizing and the P&O algorithm.

Figures (3.9) and (3.10) depict the output voltage and current of the PV generator, respectively. The results from both figures correlate with the MPP voltages and currents presented in Figure (3.5) and Figure (3.6).

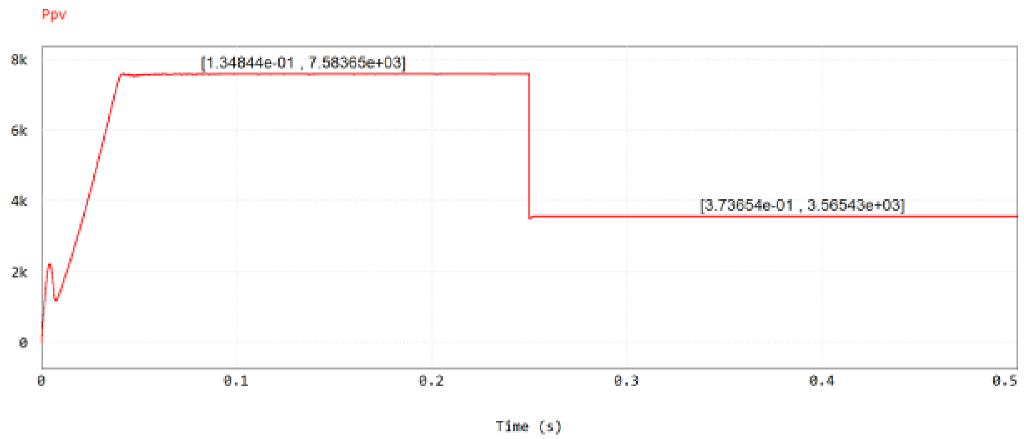


Figure 3.8. PV output power

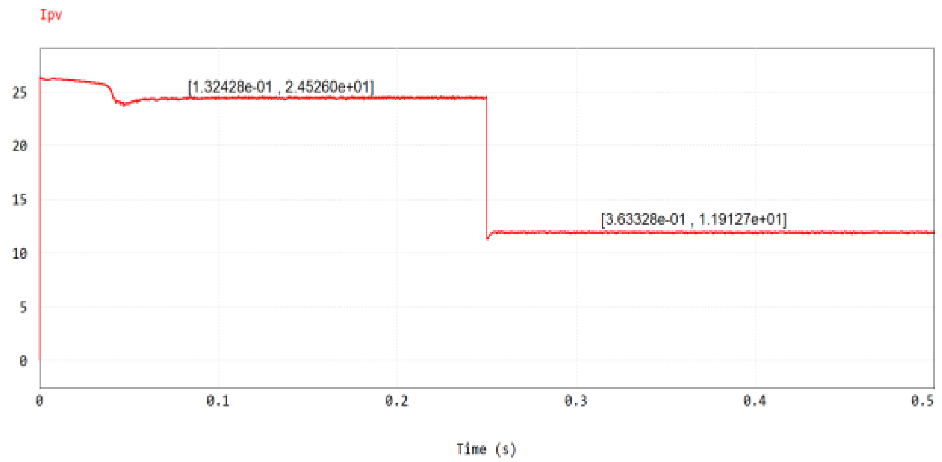


Figure 3.9. PV output current (I_{pv})

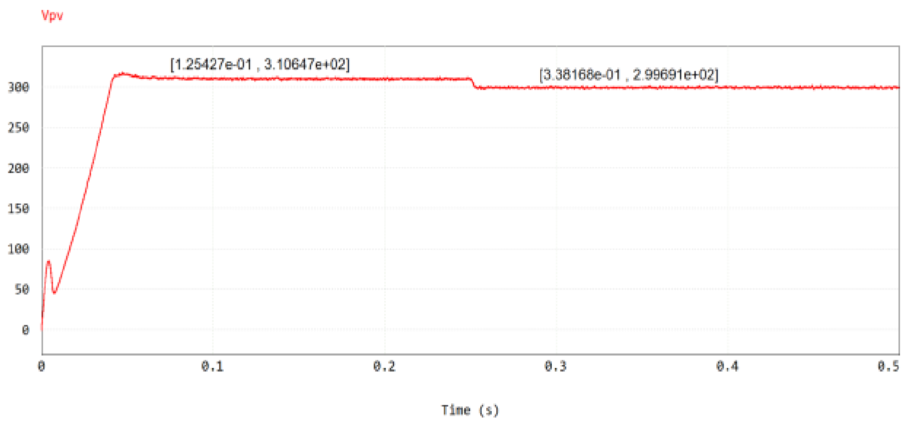


Figure 3.10: PV output voltage (V_{pv})

3.6 Grid injected active and reactive power control

In a grid-connected PV system, the main goal is to efficiently transfer all the power extracted from the PV generator to the grid. The Voltage Source Inverter (VSI) controller plays a vital role in generating the appropriate gate signals for the IGBT switches within the inverter, enabling the generation of the necessary AC voltages, currents, and power. Thus, before initiating control over the DC bus voltage, the DC bus is substituted with a DC voltage source to commence the control of active and reactive grid-injected power. Figure (3.11) depicts the electrical components of the circuit, including the C block that encompasses the control software.

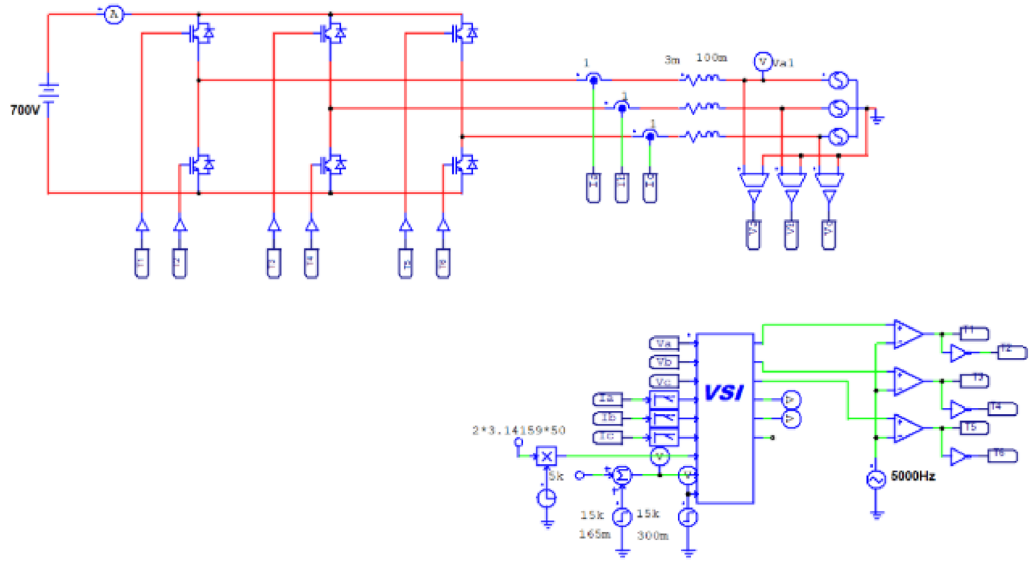


Figure 3.11. Active and reactive grid-injected power control circuit

Figure (3.12) depicts the injected current, where the curve smoothly transitions from its steady state to a transitional phase and then promptly returns to its steady state again and the Figure (3.13) depicts the injected voltage The voltage to be injected into the electrical grid exhibits sinusoidal waveforms.

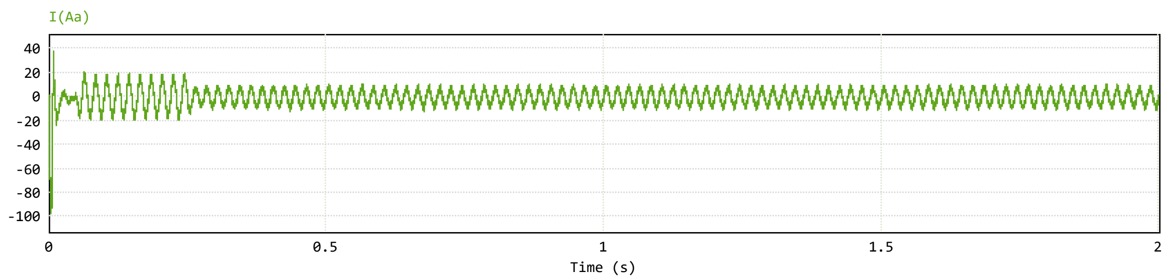


Figure 3.12. The injected current

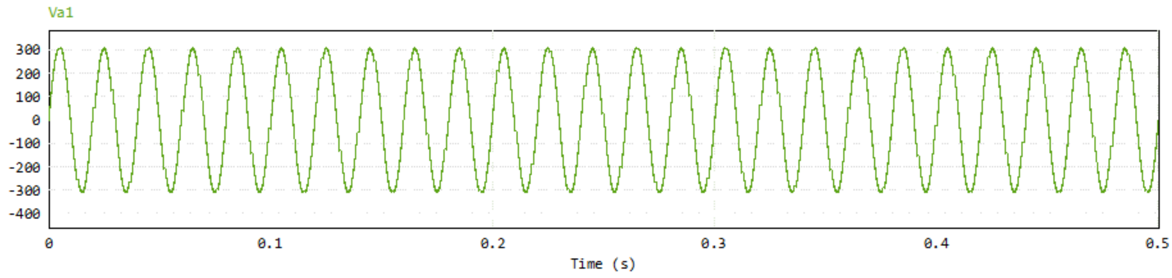


Figure 3.13. The injected voltage

The following Figure (3.14) represents the currents injected into the electrical grid.The currents exhibit nearly sinusoidal waveforms and curves smoothly transition from their steady state to a transitional phase and then promptly returns to their steady state again.

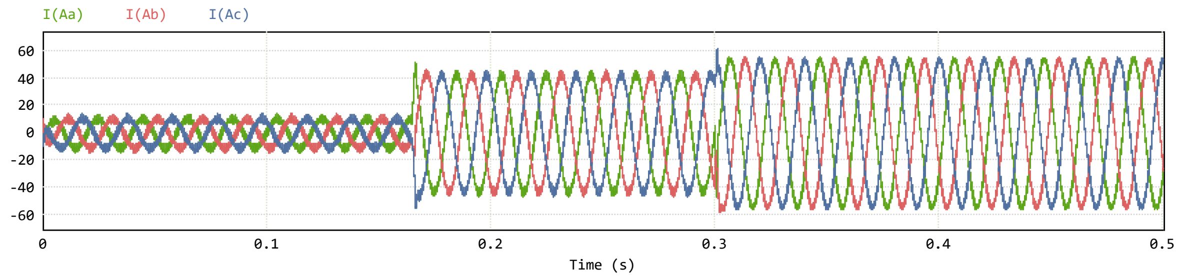


Figure 3.14. The three phases injected current

Figures (3.15) and (3.16) depict the injected active and reactive power, respectively, along with their corresponding reference values. Both figures demonstrate how the power curves closely align with their reference signals. While there are occasional instances of slight shifts in the reference signals, the power curves smoothly transition from their steady state to a transitional phase and then promptly returns to their steady state again.

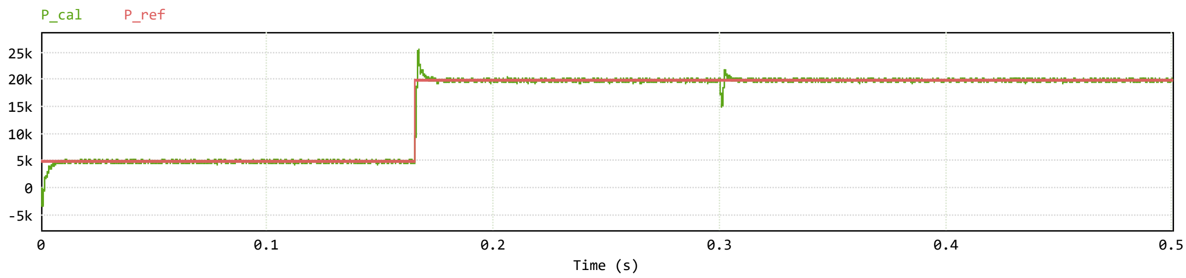


Figure 3.15. Injected active power and its reference

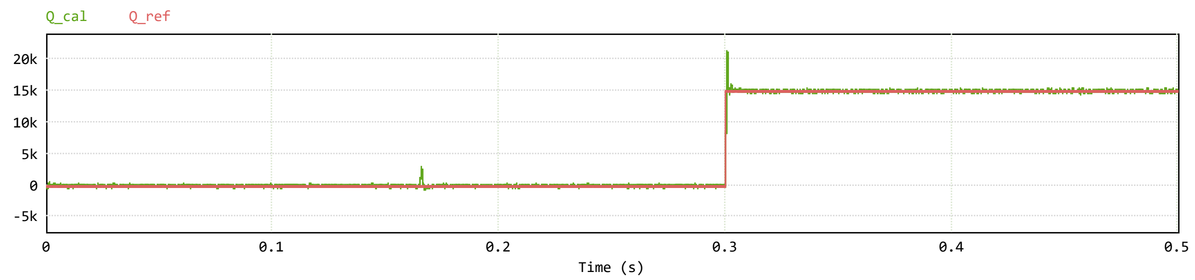


Figure 3.16. Injected reactive power and its reference

3.7 Photovoltaic grid-connected system control

The voltage source inverter is employed to convert DC power into AC power, simultaneously regulating the injected active power to uphold a constant DC bus voltage through decoupled control. By integrating both components, the transfer of maximum power provided by the PV panel to the utility grid is facilitated with optimal efficiency. The electrical circuit featuring C blocks housing the software for control algorithms is depicted in Figure (3.17).

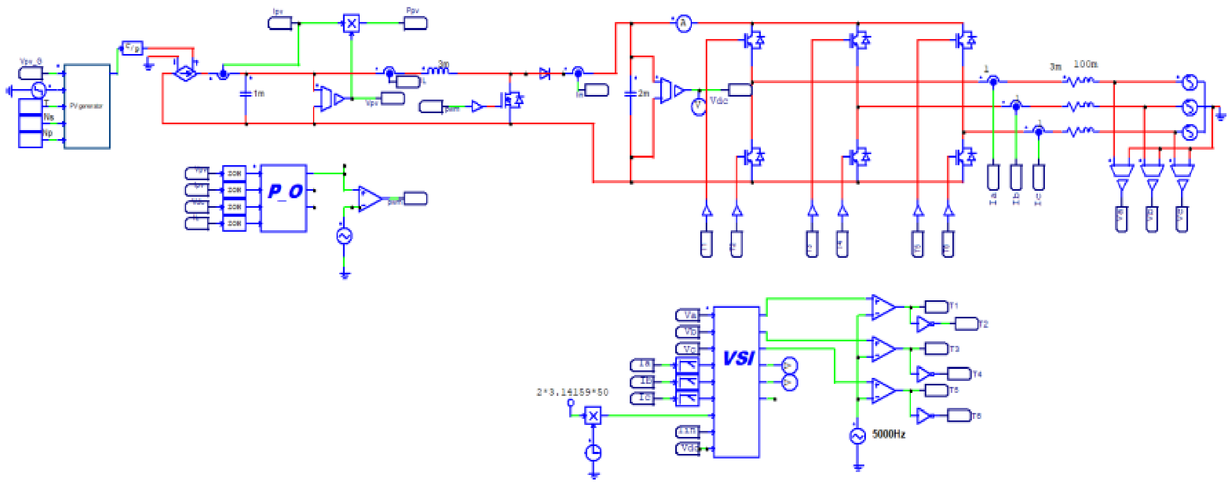


Figure 3.17. Grid-connected PV system circuit

3.7.1 .Obtained simulation results

The system represented in Figure (3.17) was simulated using the PSIM platform under two irradiance values of 1000 / 500 W/m², with each value maintained for a duration of 2.5 seconds, starting with the highest value. The results obtained after simulating the system for 56seconds are depicted in the figures below. Figure (3.18) showcases the power extracted from the PV generator, corresponding to the maximum power achievable under the two irradiance values.

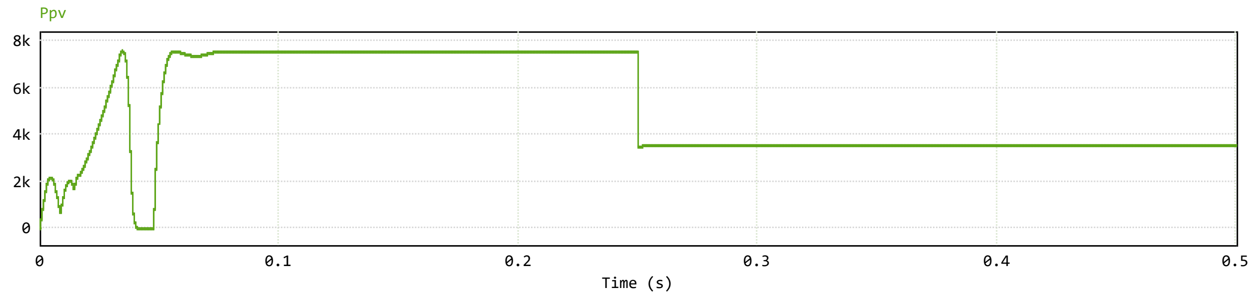


Figure 3.18: PV generator delivered power

Figure (3.19) and Figure Figure (3.20) illustrates the active power injected, its reference and reactive power, respectively. The active injected power corresponds to the power extracted from the PV generator, as depicted in Figure (3.8), with only minor shifts attributable to IGBT transitions and It corresponds also to the reference. However, the reactive power is zero, as the PV generator solely supplies active energy.

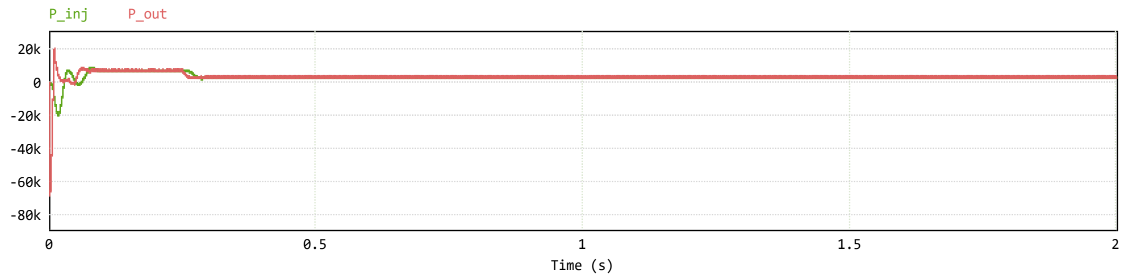


Figure 3.19: Injected active power and its reference

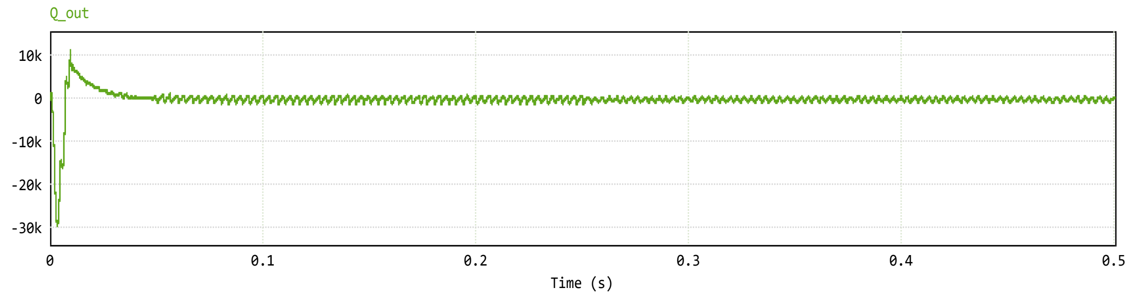


Figure 3.20. Reactive power

Figure (3.21) displays the DC bus voltage maintained at a reference voltage of 700V with an error of 2V, unaffected by the fluctuations in PV generator output current occurring at the 2.5-second mark, as illustrated in Figure (3.8).

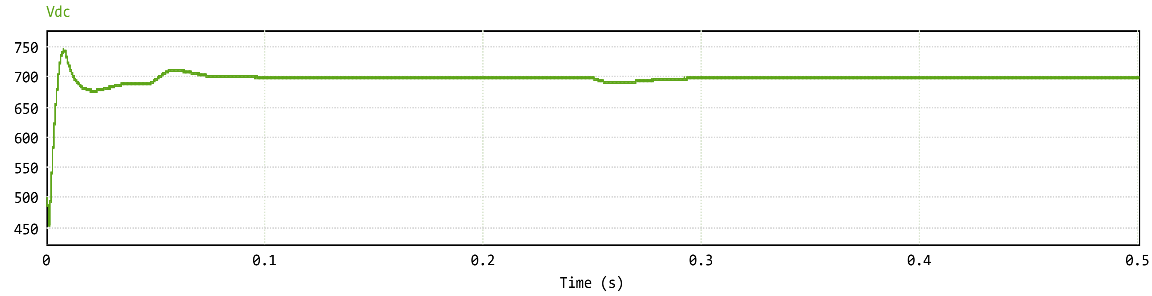


Figure 3.21. DC bus voltage

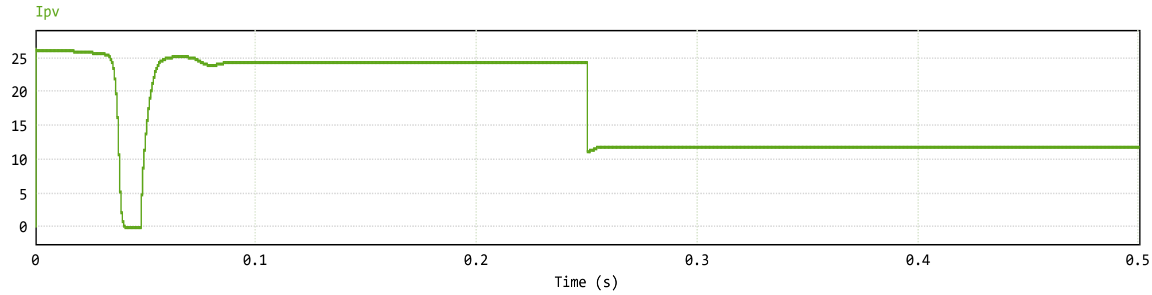


Figure 3.22. PV generator output current

Figure (3.23) illustrates the three-phase current injected into the grid. The currents exhibit nearly sinusoidal waveforms and mirror the values of the extracted current from the PV generator shown in Figure (3.22).

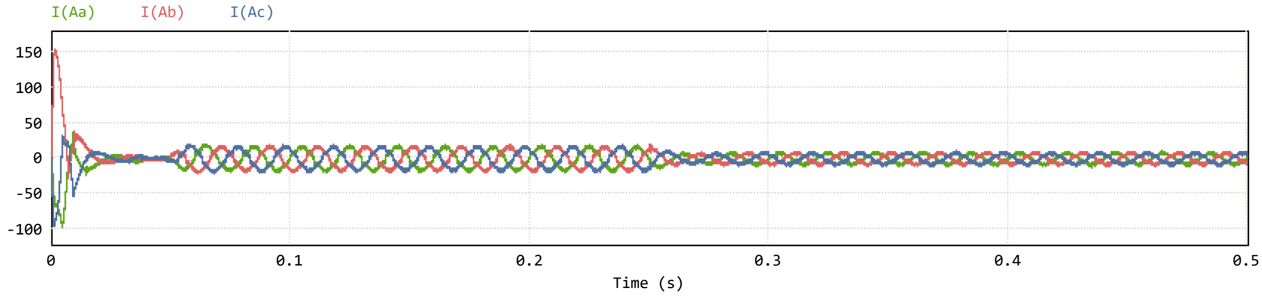


Figure 3.23. Grid injected current

3.8 Grid injected active and reactive power control with pill Technic (LAUNCHXL-F28379D) on the loop

3.8.1 Theoretical aspect

3.8.1.1 Definition

The LAUNCHXL-F28379D is a development kit produced by Texas Instruments, specifically designed for their C2000 Piccolo microcontrollers. It's a comprehensive kit that includes everything developers need to start prototyping and experimenting with the C2000 Piccolo microcontrollers, which are particularly suited for real-time control applications like motor control, power conversion, and others. The LAUNCHXL-F28379D provides easy access to the various peripherals and features of the microcontroller, making it an excellent platform for both beginners and experienced developers working on embedded systems and control applications

Figure 3.24: LAUNCHXL-F28379D

2.8.1.2 The applications of LAUNCHXL-F28379D

The LAUNCHXL-F28379D, also known as the F28379D LaunchPad, is utilized primarily for developing and prototyping applications that require real-time control, such as motor control, power conversion, digital power supplies, and various industrial automation systems. Here are some common applications and industries where the LAUNCHXL-F28379D can be utilized

1. Motor Control Systems:

- **AC Induction Motors:** Used for speed and torque control in industrial motors.
- DC Motors: Used for speed regulation and energy efficiency in industrial and commercial applications.

-Brushless DC (BLDC) Motors: Provides high efficiency and precise control in electric appliances such as fans and pumps.

-Stepper Motors: Enables precise position control in applications like 3D printers and CNC machines.

2. Digital Power Conversion:

- Inverters: Converts energy from renewable sources like solar and wind power.

-Converters: Manages different voltage levels in power distribution systems.

- Uninterruptible Power Supply (UPS) Systems: Ensures stable power supply during electrical outages.

3. Renewable Energy Systems:

- Solar Inverters: Converts captured solar energy into usable electrical power or for storage.

- Wind Turbine Control: Enhances the efficiency of energy production from wind turbines.

4. Industrial Automation and Process Control:

- Industrial Process Control Systems: Ensures efficient and accurate operation of industrial equipment.

- Automation in Production Lines: Improves production speed and reduces errors.

5. Robotics:

- Industrial Robots: Enhances performance in tasks such as assembly, welding, and packaging.

- Home Robotics: Improves efficiency in smart home devices like robotic vacuum cleaners.

6. Medical Devices:

- Medical Diagnostic Equipment: Improves accuracy and speed in devices like scanners and blood analyzers.

- Medical Therapeutic Equipment: Provides precise control in devices used for physical therapy and life-supporting equipment.

These applications leverage the F28335 Delfino's capabilities in fast and precise processing, and its support for multiple peripherals, making it an excellent choice for tasks requiring high precision and rapid response.

3.8.2 Practical aspect

Photovoltaic grid-connected system control with pill Technical (LAUNCHXL-F28379D.)

3.8.2.1The operation of LAUNCHXL-F28379D.

The LAUNCHXL-F28379D microcontroller is known for its real-time control capabilities, making it suitable for applications that require precise timing and responsiveness. Developers leverage the built-in features of the microcontroller, such as its high-resolution pulse-width modulation (PWM) modules, high-speed analog-to-digital converters (ADCs), and specialized control peripherals to implement control algorithms.

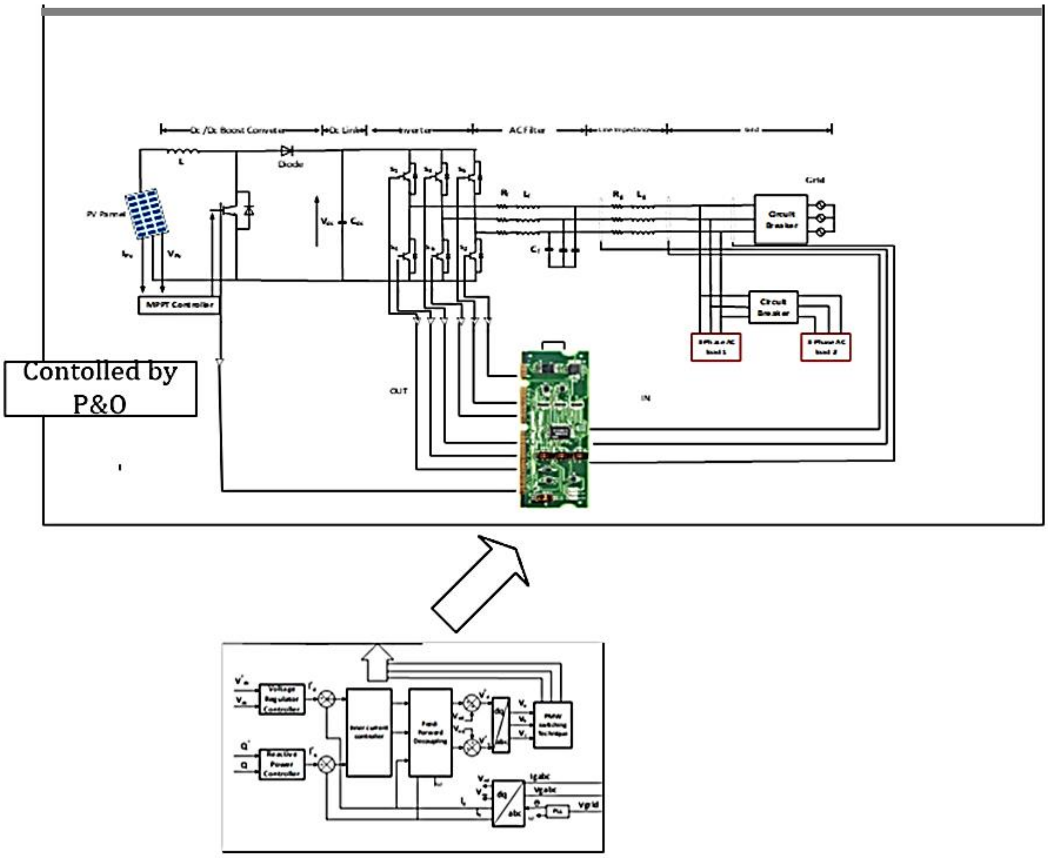


Figure 3.25: PV grid-connected system controlled by the pill Technic (LAUNCHXL-F28379D.)

3.8.2.1 The results of PV grid-connected system control with pill Technic (LAUNCHXL-F28379D.)

As we can see, the photovoltaic system connected to the electrical grid and controlled by the microcontroller LAUNCHXL-F28379D., as shown in the diagram

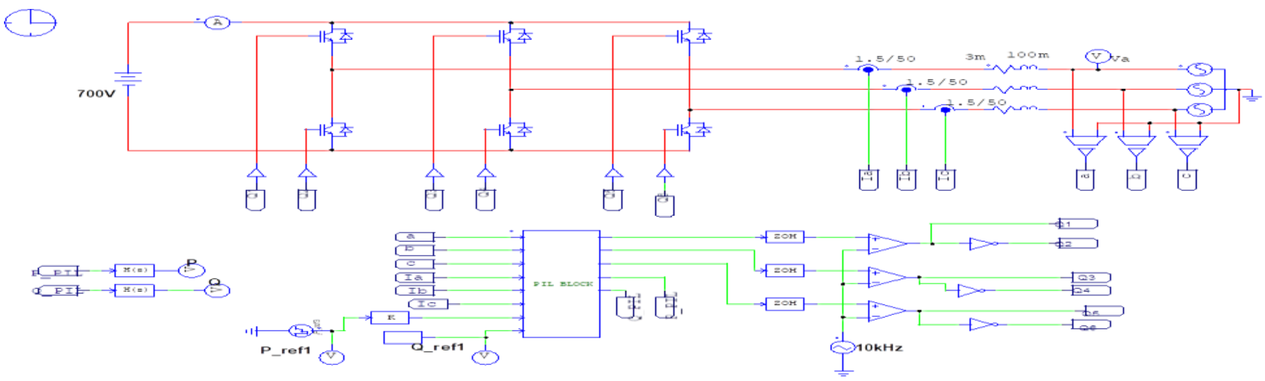


Figure 3.26: Grid-connected PV system circuit control with pill Technic (LAUNCHXL-F28379D.)

Figures (3.27) and (3.28) illustrate the injected active and reactive power and their reference signals . The injected active power corresponds to the power extracted from the PV generator, with only minor variations due to IGBT transitions, and it aligns with the reference value. However, the reactive power is zero since the PV generator provides only active energy, and the injected reactive power corresponds to the power extracted from PWM.

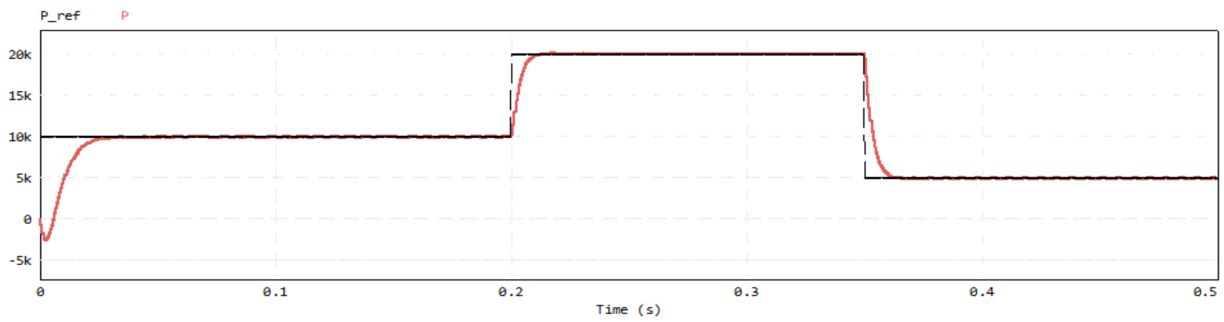


Figure 3.27. Injected active power and its reference

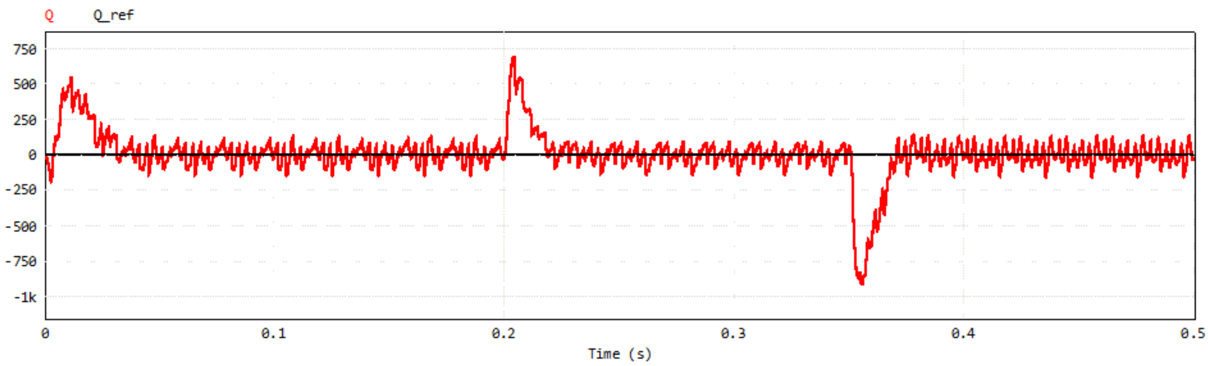


Figure 3.28. Injected reactive power and its reference

Figure (3.29) illustrates the injected current, showing a smooth transition of the curve from its steady state to a transitional phase and then promptly returning to its steady state again. In Figure (3.30), the injected voltage into the electrical grid is depicted, exhibiting sinusoidal waveforms.

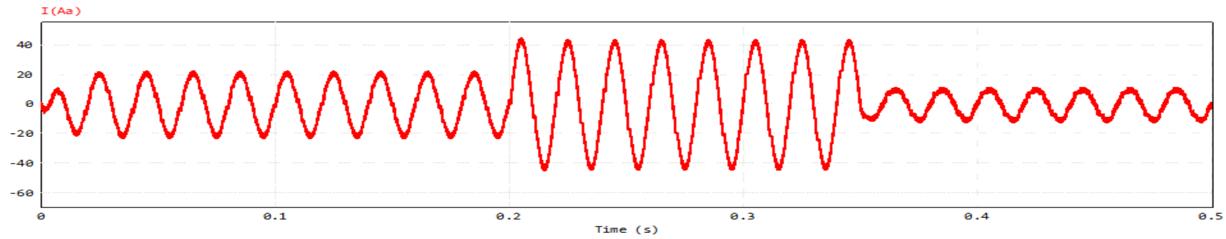


Figure 3.29. Grid injected current

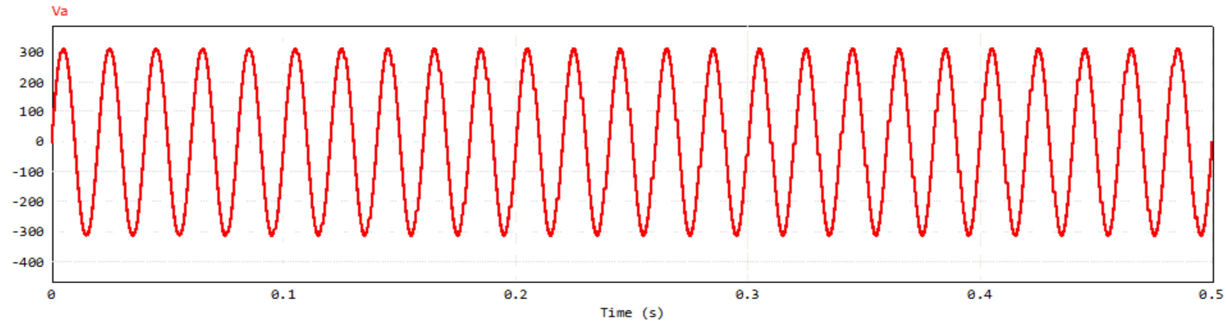


Figure 3.30. Grid injected voltage

Figure (3.31) depicts the three-phase current injected into the grid. The currents display almost sinusoidal waveforms and align with the values of the extracted current from the PV generator depicted in Figure (3.22). These results also correlate with those obtained from PSIM.

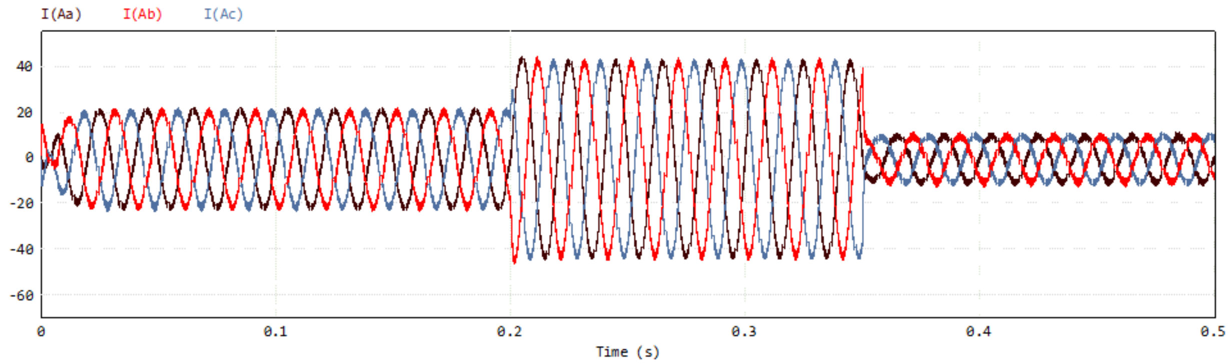


Figure 3.31: Grid injected current

Conclusion

In this chapter, we conducted simulations using the PSIM platform to analyze a grid-connected PV system, yielding valuable results. Our main objective was to simulate each component of the system independently. Initially, we simulated the implementation of a maximum power point tracking method to optimize power extraction from the PV generator. Subsequently, we simulated the second part of the system, which focused on controlling the injected active and reactive power. The latter part of this chapter was dedicated to simulating the integrated system as a whole. We utilized two different irradiance values, aligning the extracted power with the maximum power point of the PV generator. Ultimately, this optimized power was effectively injected into the main grid, Subsequently, we simulated the system externally using pill technic LAUNCHXL-F28379D

General conclusion

The research presented in this thesis focuses on modeling and controlling a grid-connected photovoltaic system. This system has significant development potential, driven primarily by an increasing commitment to diversifying electrical energy production methods and transitioning towards renewable energy sources. To facilitate comprehension, the dissertation is structured into three chapters. The second chapter delves into converter control within a grid-connected photovoltaic system. It provides an overview of this system, discussing the definition of DC-DC converters and reviewing various types. The principle and modeling of the boost converter are presented, along with the definition and classification of inverters. The chapter examines three-phase inverters, discussing their modeling, pulse width modulation (PWM) principles, and various maximum power point tracking (MPPT) methods, with a focus on the perturb and observe algorithm. It concludes by discussing inverter control using voltage source inverter (VSI) and phase-locked loop (PLL) techniques. Towards the conclusion of the study, the grid-connected photovoltaic system is simulated and controlled using the PSIM software platform. Each system component is individually simulated, and the results are analyzed. Subsequently, the entire system is simulated to evaluate its overall performance In the end, the LAUNCHXL-F28379D is connected for external system simulation. Simulation results confirm the effectiveness of the proposed grid-connected PV system in efficiently injecting maximum extracted power into the main grid.

SUMMARY

This study presents the modeling and control of a grid-connected photovoltaic system, providing a comprehensive overview of its key components such as the photovoltaic array, boost converter, and grid-connected inverter. Effective control strategies were devised for the DC/DC converter to enhance power extraction from the photovoltaic generator. The inverter ensures seamless power transfer to the grid while maintaining a consistent DC bus voltage. Simulation results obtained using PSIM software validate the efficacy of these control methods for grid-connected photovoltaic systems.

Keywords: Photovoltaic - Boost converter - Inverter - Grid - MPPT --PWM

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Abstract

This work presents a simulation model of the electrical part of a grid-connected photovoltaic generator. The model includes a detailed representation of the main components of the system, which are the solar array, boost converter, and grid-connected inverters. An appropriate control for the DC/DC converters has been developed to extract the maximum amount of energy from the photovoltaic generator. The grid-connected inverter transfers the energy drawn from the photovoltaic unit into the grid by maintaining a constant common DC voltage. The modeling and control are carried out using the causal informational graph method. The simulation results using PSIM show the control performance and dynamic behavior of the grid-connected photovoltaic system. Then, the grid-connected system was interfaced with the LAUNCHXL-F28379D board for external simulation.

Résumé

Ce travail présente un modèle de simulation de la partie électrique d'un générateur photovoltaïque connecté au réseau. Le modèle inclut une représentation détaillée des principaux composants du système, à savoir le panneau solaire, le convertisseur élévateur et les onduleurs connectés au réseau. Un contrôle approprié des convertisseurs DC/DC a été développé afin d'extraire la quantité maximale d'énergie du générateur photovoltaïque. L'onduleur connecté au réseau transfère l'énergie tirée de l'unité photovoltaïque vers le réseau en maintenant une tension DC commune constante. Les résultats de la simulation utilisant PSIM montrent la performance du contrôle et le comportement dynamique du système photovoltaïque connecté au réseau. Ensuite, le système connecté au réseau a été interfacé avec la carte LAUNCHXL-F28379D pour une simulation externe.

الملخص

تقدم هذه الورقة نموذج محاكاة للجزء الكهربائي من مولد كهروضوئي متصل بالشبكة. يشمل النموذج تمثيلاً تفصيلياً للمكونات الرئيسية للنظام، وهي مجموعة الألواح الشمسية، محول الرفع، والمحولات المتصلة بالشبكة. تم تطوير نظام لاستخراج أكبر قدر ممكن من الطاقة من المولد الكهروضوئي. يقوم المحول المتصل بالشبكة بنقل الطاقة المستمدة من الوحدة الكهروضوئية إلى الشبكة من خلال الحفاظ على جهدDC مشترك وثابت .يتم تنفيذ النمذجة والتحكم باستخدام طريقة الرسم البياني المعلوماتي ،تظهر نتائج المحاكاة باستخدام PSIM أداء التحكم والسلوك الديناميكي للنظام الكهروضوئي المتصل بالشبكة ومن ثم تم ربط النظام المتصل بالشبكة بالبطاقةLAUNCHXL-F28379D لمحاكاة النظام خارجيا.