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BAKHTAOUI djamila **ALLAL siham**

Title

Modeling and control of a grid-connected photovoltaic system

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We would also like to thank the esteemed committee members for their interest in our work, for accepting to review our thesis, and for their valuable contributions in evaluating it.

DEDICATION

Praise be to Allah. What has ended is a journey, neither difficult nor impossible except by Your guidance, generosity, and grace upon me.

O Allah, it is not by my effort or striving, but only by Your facilitation, favor, and grace upon me.

*To my angel in life and to the dearest ones, **my beloved mother***

*And to the shield of my back and support, **my father**. To **my sisters and brother**..*

To all my colleagues and companions with whom I have shared my educational journey. To everyone whom destiny has brought together, be it relatives, friends, and all those who have extended a helping hand, whether near or far.

. O Allah, make easy and facilitate for me what comes next and open for me from Your doors

BAKHTAOUI djamila

DEDICATION

The journey was not short, and it should not have been, as the dream was not close, and the road was not paved with ease. However, I did it.

To the unseen hand and the constant support in every moment I've experienced, to ***my beloved mother****.*

After the grace of God, to my siblings ***Aya, Nihal, Anas, and Benyahia,*** *and to the companions of the years, and to everyone who has been a help and support on this journey.*

ALLAL siham.

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GENERAL INTRODUCTION

The use of renewable energies is experiencing significant growth worldwide, driven by the increasing demand for electrical energy, especially in remote regions lacking reliable electricity, such as deserts and mountainous areas. A large portion of the consumed energy comes from fossil fuels (oil, natural gas, coal, etc.), whose massive utilization can lead to the depletion of these reserves and pose a real threat to the environment, primarily through pollution and global warming of the earth [13].

Today, there are several types of renewable energy sources distinguished: hydroelectric energy, geothermal energy, biomass energy, wind energy, and photovoltaic energy. The main advantage of these renewable energies is that their use does not pollute the atmosphere, and they do not produce greenhouse gases such as carbon dioxide and nitrogen oxides, which are responsible for global warming [13].

Photovoltaic solar energy is a form of renewable energy that allows electricity production by converting a portion of solar radiation using photovoltaic solar modules, comprising several interconnected photovoltaic cells. The local impacts of solar energy are minimal: no noise, no emissions, and visually, they can be discreet and even elegant for some building-integrated structures [13].

Photovoltaic energy is derived directly from the radiation of the sun. Through the photovoltaic effect, this energy can be converted into electrical energy. photovoltaic panels consist of photovoltaic cells that possess the capability to convert photons into electrons. As a result, the energy is generated in the form of direct current, which can be readily utilized.
In this dissertation, our study focuses on the photovoltaic sector and primarily involves modeling and controlling a grid-connected photovoltaic system[13].

Then, organized our work in three chapters as follows:

The first chapter provides an introduction to the photovoltaic system. It begins with an overview of photovoltaic energy, followed by an explanation of the photovoltaic effect and the principles of photovoltaic conversion. Next, various types of photovoltaic cells, their characteristics, and modeling techniques are presented. The third section of this chapter focuses on the definition of a photovoltaic generator, exploring the influence of sunlight and temperature on its performance. Additionally, the different components of a photovoltaic system are discussed, along with an overview of its classification. This chapter concludes by addressing the quality and standards of grid-connected systems, as well as highlighting advantages and disadvantages of PV system.

In the second chapter,is dedicated to the control of grid-connected photovoltaic system converters. It begins with an exploration of the configuration of grid-connected photovoltaic generation, followed by an examination of different 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. This is followed by an introduction to the Maximum Power Point Tracking (MPPT) control, including its definition, methods, and the characteristics of different MPPT methods. The chapter concludes with a mention of Voltage Source Inverter (VSI) control and its associated phase-locked loop (PLL) control.

The final chapteris devoted to the simulation and results of the studied system. It begins with the simulation results of the panel characteristics and the photovoltaic generator. Then, the results of the boost control of the converter using the P and O (Perturb and Observe) algorithm will be presented. Additionally, the simulation results of the inverter with VSI control will be discussed. This chapter will be concluded with the simulation results of the overall photovoltaic system connected to the grid.

Finally , concluded our work with a general conclusion. .

CHAPTER 1

INTRODUCTION TO PHOTOVOLTAIC SYSTEM

Introduction

Every day, the sun generously supplies the Earth with abundant energy. This immense resource can be effectively harnessed through the utilization of photovoltaics, a technology that converts solar energy into electricity. Photovoltaic (PV) technology, also known as solar electric, is recognized as one of the most innovative and swiftly expanding renewable energy resources employed for electricity generation on a global scale. The adoption of PV technology offers a multitude of advantages, including its enduring nature, universal availability, eco-friendliness, affordability, absence of pollution, and minimal maintenance requirements [14].

The applications of photovoltaic systems encompass a wide range of energy services, catering to both remote areas and network utilities. These applications include providing lighting to villages, powering solar home systems, illuminating streets and camps, facilitating traffic management, supporting medical facilities in remote regions, enabling telecommunication stations, facilitating battery charging, and operating water pumping and purification systems. The utilization of photovoltaic systems for electricity production originated in the 1970s and has since experienced substantial global growth, despite initial high capital costs [15].

This chapter is devoted to the introduction of photovoltaic systems. we present the definition of photovoltaic energy and explain the photovoltaic effect. The principle of photovoltaic conversion is discussed, along with the types and characteristics of photovoltaic cells. We also cover the modeling of photovoltaic cells and the model of PV generators. Furthermore, we discuss the classification and components of PV systems, as well as the quality and standards of grid-connected systems. Finally, we conclude by highlighting the advantages and disadvantages of photovoltaic systems.

1.1 Photovoltaic energy

1.1.1 Definition

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

1.2 The photovoltaic effect

The photovoltaic effect is a process of transforming the energy emitted by the sun, in the form of photons, into electrical energy using a semiconductor component called solar cell [16]. This operation is done in three steps:
a-Absorption of photons from sunlight.
b-Conversion of the energy received by the photons into electrical energy.
c-Aggregation of particles in an external electrical circuit.

1.3 The principle of photovoltaic conversion

How does a photovoltaic solar cell work?
The photovoltaic cell comprises a semiconductor material that plays a crucial role in its functioning. When photons interact with a PV cell, they can either reflect off the cell, pass through it, or be absorbed by the semiconductor material. Only the absorbed photons provide the necessary energy to generate electricity. As the semiconductor material absorbs sunlight (solar energy), electrons become dislodged from the atoms within the material. Through specific treatments applied to the material surface during manufacturing, the front surface of the cell is made more receptive to these dislodged electrons, allowing them to naturally migrate towards the surface of the cell [13].
By establishing a circulation of electrons in the external circuit, the photovoltaic cell operates as a generator. The voltage produced by the cell typically ranges between 0.3 V and 0.7 V, depending on factors such as the material used, its arrangement, and the temperature of the cell.

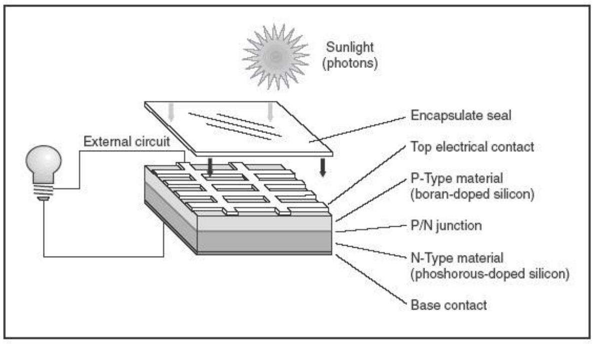

Figure 1.1: photovoltaic cell structure

1.3.0.1 Type of photovoltaic cells

The cell is the most suitable conversion unit for the photovoltaic effect. The materials and the methodology used for the design of these cells influence the recovered energy. As a result, many solutions have been developed and they will be briefly introduced in next subsections.

a) Monocrystalline Silicon

Among the photovoltaic cells using silicon as base material, the monocrystalline are, in general, those which have the best performances. Thus, the commercial solar cells obtained with this process can reach an efficiency of 15 to 18% [17].

b) Polycrystalline Silicon

Polycrystalline silicon cells are cheaper than monocrystalline ones because the cell manufacturing processes are less stringent. However, their efficiency is lower. The manufacturing process is similar to the one previously described for silicon cell production but with less rigorous control.As a result, the cells obtained are less expensive but also less efficient (12.5% on average)[17].

c) Amorphous silicon

The use of amorphous silicon for solar cells has demonstrated significant advantages in terms of both electrical properties and the manufacturing process. It offers a simple production process, low energy consumption, cost-effectiveness, and the ability to produce cells with large areas. However, despite the reduced production cost, amorphous silicon solar cells have two disadvantages. Firstly, they exhibit lower conversion efficiency compared to monocrystalline and polycrystalline silicon cells. Secondly, Their performance decreases rapidly by 10% to 20% of their power during the first three to six months of operation.

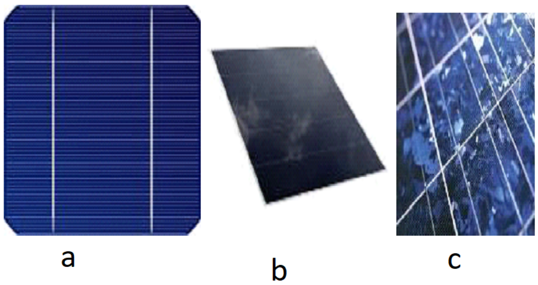

Figure 1.2: Type of photovoltaic cells

1.3.1 Electrical characteristics of photovoltaic cell

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

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

   The short-circuit current is the maximum current generated by the cell when it is subject to a short-circuit (V = 0) for "full sun" illumination, It is directly proportional to the radiant energy received on the surface of the cell. Its value is obtained by connecting an ammeter across the cell terminals. Since Rs , Rsh, it can obtained Icc = Iph [18].

2. **Open circuit voltage Voc (for Isc = 0) :**

The open circuit voltage, Voc, refers to the voltage across the terminals of the cell when no load is connected, resulting in a generated current (I) of 0. By neglecting the current flowing through the parallel resistor Rsh, the Voc can be determined by directly connecting a voltmeter to the terminals of the cell.

3. **Maximum Power Point (MPP)**:

The crucial section of the I-V characteristic for users is the one that corresponds to energy generation. This point does not lie at the open circuit voltage (Voc) or the short-circuit point since they do not generate any power. Considering that power is the product of voltage and current (P = V × I), the maximum power point (Vmp, Imp) represents the operating point where the power supplied to the load is at its highest [19].

$$P_{mp} = V_{mp}I_{mp} \tag{1.1}$$

Where Pmp = maximum power point,‘
Vmp = maximum power voltage,
Imp= maximum power current.

4. **Fill factor (FF)**:

It is an important parameter in assessing the performance of a solar cell. It is calculated as the ratio of the maximum power of the solar cell to the product of the open-circuit voltage (Voc) and short-circuit current (Isc). It typically has a value of around 0.7 for efficient cells and decreases with temperature [18]. The expression for the fill factor is given by:

$$FF = \frac{V_{mp}I_{mp}}{v_{oc}I_{cc}}V_{mp}.I_{mp} \tag{1.2}$$

Where Voc = open circuit voltage,
Icc = short circuit current.

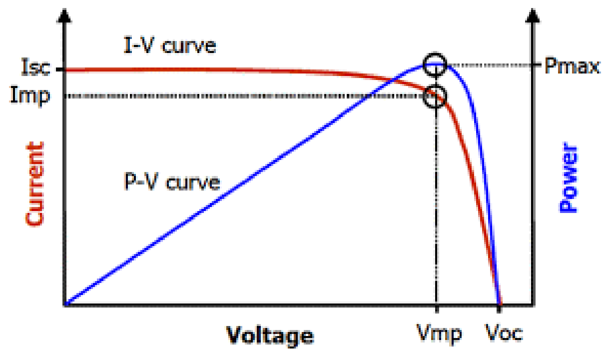

Figure 1.3: Typical I-V and P-V characteristics of photovoltaic cell

1.3.2 Modeling of PV cells

1.3.2.1 Modeling of Single-Diode solar cell

Three equivalent circuit models can be used to single-diode model :

1. Ideal solar cell or the single mechanism, three parameters (1M3P) model.
2. Solar cell with series resistance or the 1M4P model.
3. Solar Cell with Series and shunt resistances, also known as the 1M5P model.

1. Ideal Solar Cell (1M3P)

The ideal equivalent circuit of a solar cell is a current source in parallel with a single diode. This model involves three unknown parameters: V (open-circuit voltage), Iph (short-circuit current), and Is (diode saturation current). This model is also known as the 1M3P model [20]. The configuration of the ideal solar cell model with a single-diode is shown in Figure (1.4)

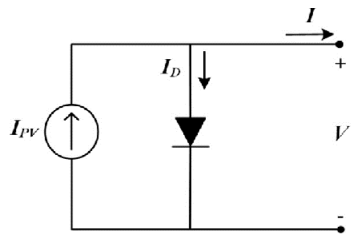

Figure 1.4: circuit the ideal model

The characteristic equation is deduced directly from the Kirchhoff law:

$$I_{pv} = I_{ph} I_d \tag{1.3}$$

Where
Ipv = photovoltaic current,
Iph =photon current,
Id = diode current. The diode current is given by the following equation: law:

$$I_d = I_s(e^{\frac{qv_{pv}}{mkT}} - 1) \tag{1.4}$$

Where
Is = series current , q = electric charge (1.6*10-19C), m = diode quality factor,
K = Boltzmann constant (1.3854*10-23 J/K),
T = temperature ,
Vpv = photovoltaic voltage.
So the output current is presented by the following non linear I-V equation

$$I_d = I_{ph} - I_s(e^{\frac{qv_{pv}}{mkT}} - 1) \tag{1.5}$$

For the same irradiation and PN junction temperature conditions, the short-circuit current Isc is the greatest value of the current generated by the cell and the open circuit voltage Voc is the greatest value of the voltage at the cell terminals:

$$I_{sc} = I_{ph} = I_{pv} for V_{pv} = 0 \tag{1.6}$$

$$V_{pv} = V_{oc} = \frac{mkT}{q} ln(1 + \frac{I_{sc}}{I_s}) \tag{1.7}$$

The output power is :

$$P = V_{pv}[I_{sc} - I_s(e^{\frac{qv_{pv}}{mkT}} - 1)] \tag{1.8}$$

2. Solar Cell with Series Resistance:

More accuracy can be introduced to the model by adding a series resistance. The electric schematic equivalent to this model is shown in Figure(1.5) This model involves the following four unknown parameters (V, Iph, Rs, and Is), which is also called 1M4P [21].

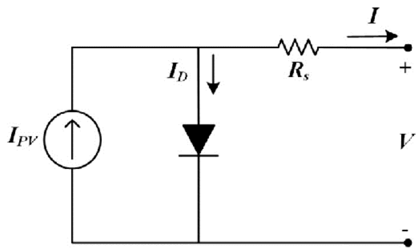

Figure 1.5: Circuit model 1M4P

The diode current is:

$$I_d = I_s(e^{\frac{qv_{pv}+R_sI_{pv}}{mkT}} - 1)] \quad (1.9)$$

Where

Rs = series resistance. Therefore, the I-V characteristic of the solar cell with single-diode and series resistance is given by:

$$I_{pv} = I_{ph} - I_s(e^{qv_{pv}+R_sI_{pv}} - 1)] \quad (1.10)$$

3. Solar Cell with Series and Shunt Resistances (1M5P):

The losses in this configuration are modeled by two resistances: shunt resistance and series resistance. Thus, the model involves the following five unknown parameters (V, Iph, Rs, Rsh, and Is). This model is also called 1M5P, and its electrical schematic is shown in Figure(1.6)

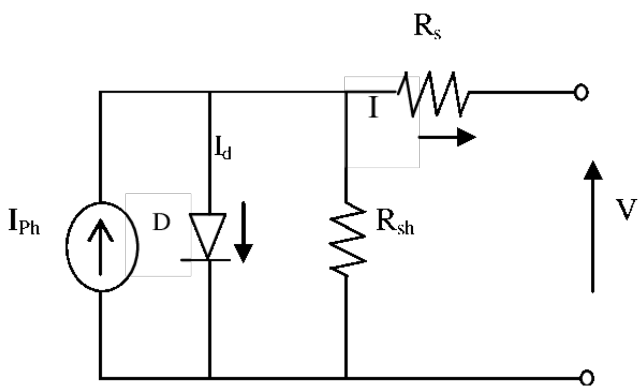

Figure 1.6: Circuit of model 1M5P

The characteristic equation can be deduced directly by using the Kirchhoff law:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1.11)$$

Where

Ish = shunt current The diode current is:

$$I_d = I_s(e^{\frac{qv_{pv}+R_sI_{pv}}{mkT}} - 1)] \quad (1.12)$$

The shunt current is:

$$I_{sc} = \frac{V + R_sI_{pv}}{R_{sh}} \quad (1.13)$$

The single-diode model is governed by the following equation:

$$I_{pv} = I_{ph} - I_s(e^{qv_{pv}+R_sI_{pv}} - 1) - \frac{V + R_sI_{pv}}{R_{sh}} \tag{1.14}$$

Where

Rsh = shunt resistance.

The modeling of the PV cell in the three cases was done by applying the previous equations. Many types of simulation are carried out depending on the chosen model and the selected parameters [22].

1.3.2.2 Modeling of two-diodes solar cell

The two-diode model of the solar cell provides a high level of accuracy, although it is somewhat more complex. The configuration of this model is shown in Figure(1.7) [23]. The two-diodes model is governed

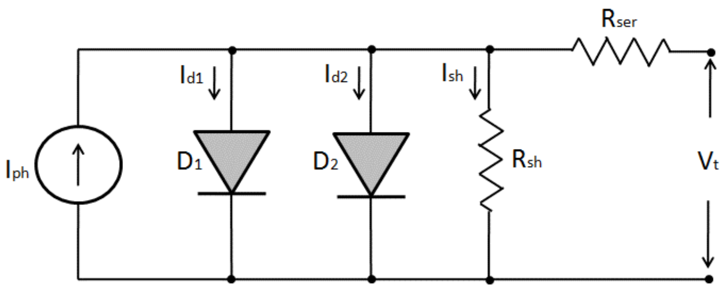

Figure 1.7: Equivalent circuit of two diodes model

by the following equation

$$I_{pv} = I_{l.ph} - I_{1.pv}(e^{\frac{v_{pv}+R_sI_{pv}}{vt1}} - 1) - I_{2.pv}(e^{\frac{v_{pv}+R_sI_{pv}}{vt2}} - 1) - \frac{V_{pv} + R_sI_{pv}}{R_{sh}} \tag{1.15}$$

Where

I02 = first diode saturation current 1,

I02 = two diode saturation current,

Vt2 = the instant temperature voltage.

1.4 Model of the photovoltaic generator

A photovoltaic generator consists of a modules, which are formed by of photovoltaic cells, these modules are connected together in series and in parallel to generate the necessary current and voltage. The temperature plays an important role in the PV generator performances. Therefore, it is necessary to have a thermal model for a PV cell/module [24]. Figure (1.8) shows the model of PV generator.

1.5 Influence of irradiation and temperature on the PV module

1.5.1 Influence of irradiation

Figure(1.9) illustrates the relationship between the P-V (power-voltage) and I-V (current-voltage) properties under varying temperature and irradiation levels. From the curves, it can be observed that as the irradiation increases, the current also increases, leading to an increase in the maximum power point [2].

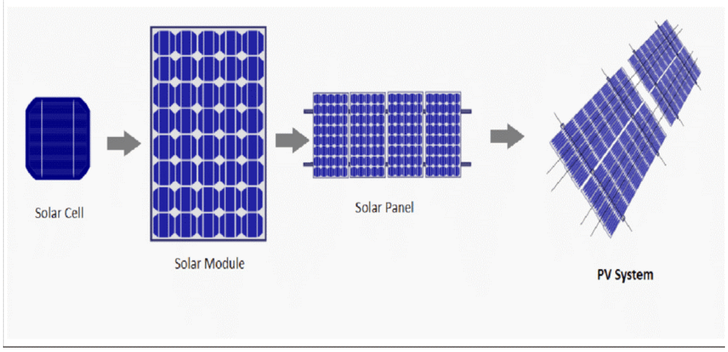

Figure 1.8: Model of photovoltaic generator [1]

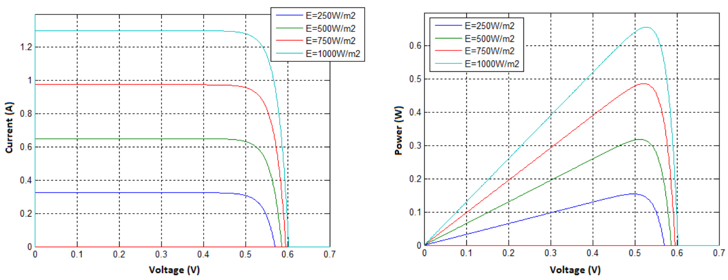

Figure 1.9: Influence of irradiation [2]

1.5.2 Influence of temperature

Temperature is a crucial parameter that significantly affects the performance of PV cells. Figure **??**llustrates the behavior of a module under a fixed illumination of 1000W/m2, with temperatures ranging from 0°C to 75°C. It can be observed that there is a slight increase in current with higher temperatures, while the open circuit voltage decreases. This decrease in open circuit voltage results in a decrease in the maximum power points [[3].

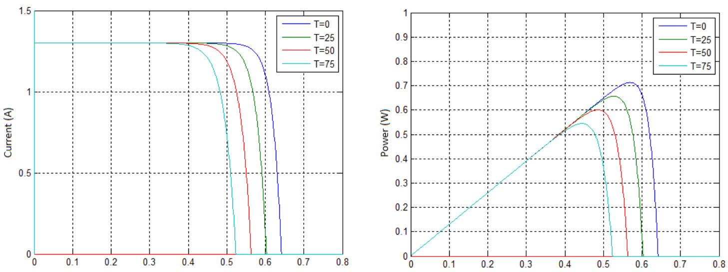

Figure 1.10: Influence of temperature [3]

1.6 Photovoltaic system components

The components of a solar energy system vary depending on the intended use, whether it's an isolated or grid-connected system. A solar energy system typically includes the following components:

- Solar cells or solar panels, which make up the photovoltaic array.
- Load controllers, which optimize the load transfer to the batteries.

- Converters, such as DC/DC or DC/AC converters, which convert the electrical energy between different forms.
- Batteries, which store the generated energy for later use.
- Additional components may also be included, depending on the specific system requirements

‘

1.7 Classification of photovoltaic systems

The photovoltaic systems are classified into two main types:
1- Stand-alone PV system;
2- Grid-connected PV system.

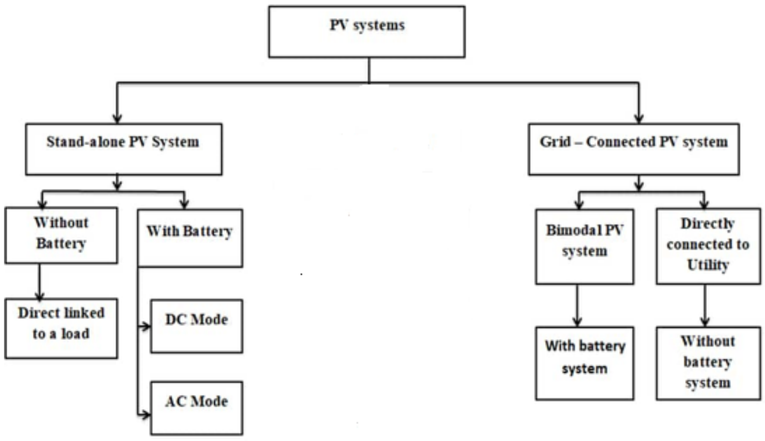

Figure 1.11: Classification of PV system.

1.7.1 Stand-alone system

This system operate independently and is not connected to the electrical grid. it typically includes solar panels, a charge controller, batteries for energy storage, and sometimes an inverter to convert DC power from the solar panels into AC power for appliances as shows in figure (1.12) [25].

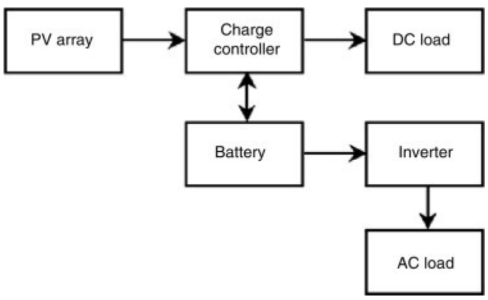

Figure 1.12: Stand-alone system

1.7.2 Grid-connected photovoltaic System

This system is connected to the electrical grid and can feed excess electricity back into the grid. It consists of solar panels, an inverter to convert DC power into AC power, and a grid interconnection device to facilitate the connection to the utility grid as shown in Figure (1.13).

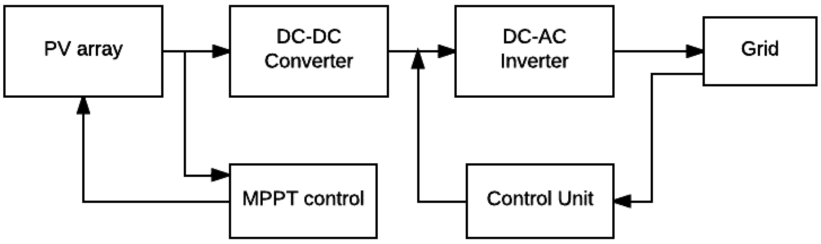

Figure 1.13: Grid-connected network System

There are two types of installations for injecting solar energy production into the electrical network:

1. Full production injection: In this type, the energy generated by the solar generators is directly injected into the electrical grid. During periods of solar energy production, the generated electricity is supplied to the grid, allowing it to be utilized by other consumers.

2. Surplus production injection: In this type, the energy produced by the solar generators is first consumed directly by the local loads or on-site consumption. Any excess energy, which exceeds the instantaneous consumption, is then injected into the local distribution network. This ensures that the surplus energy is effectively utilized and shared with other users in the network.

1.8 Quality and standards of grid-connected photovoltaic systems

The quality and standards of a grid-connected system include the following aspects [26]:

- Decoupling of the photovoltaic systems from the grid in the event of grid failure to prevent islanding issues.
- Maintaining the quality of power 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 stability of the grid by mitigating frequency fluctuations and voltage drops.

These measures are crucial to ensure the reliable and efficient integration of photovoltaic systems with the grid, minimizing any potential negative impacts on grid stability and power quality. Adhering to these standards helps maintain a stable and harmonious operation between the solar energy production and the electrical grid.

1.9 Advantages and disadvantages of photovoltaic systems

Photovoltaic systems offer numerous advantages, but they also have certain drawbacks, which are discussed in the following subsections.

1.9.1 Advantages

- Direct conversion of free and inexhaustible solar energy into electricity.
- Absence of noise, pollution, and emissions, along with reduced maintenance requirements (no

moving parts and individual module lifespan of approximately 20 years).

• Flexibility to adjust the installation size according to current needs, with the option of expansion as energy requirements increase.

• Photovoltaic systems provide added value to rural areas, particularly in developing countries where no electricity grid is available.

• Ensured profitability for low-power applications (less than 3-5 kWh/day).

1.9.2 Disadvantages

• The manufacturing of photovoltaic modules requires advanced technology and substantial investments.

• Photovoltaic generators are primarily competitive with diesel generators for low energy demands in isolated areas.

• Incorporating electrical energy storage in the form of batteries increases the cost of the photovoltaic system. However, proper selection of batteries and associated regulation components ensures reliability and performance.

• Many devices available in the market operate on alternating current at higher voltages (220-230V), whereas the power generated by the photovoltaic system is unidirectional and low voltage (<30V). Therefore, a boost/inverter conversion is required.

• High-power photovoltaic systems often require a backup system, such as a wind or diesel generator, to meet periods of high demand or during cloudy weather conditions.

It is important to consider both the advantages and disadvantages of photovoltaic systems to make informed decisions regarding their implementation. While they offer clean and renewable energy solutions, certain limitations and considerations must be taken into account to ensure optimal performance and cost-effectiveness.

Conclusion

This chapter provided an overview of photovoltaic energy, explaining the photovoltaic effect and the principle of photovoltaic conversion. It discussed various types of photovoltaic cells, their characteristics, and the modeling approaches used. Additionally, the chapter delved into the definition of a photovoltaic generator, exploring the impact of irradiation and temperature on its performance. The different components of a photovoltaic system were also examined, and the chapter concluded with a discussion on the classification of PV systems, highlighting their advantages and disadvantages. Moving forward to the next chapter, the focus will shift towards the control of grid-connected photovoltaic system converters

CHAPTER 2

GRID CONNECTED PHOTOVOLTAIC SYSTEM CONVERTERS CONTROL

Introduction

This chapter focuses on the control of grid-connected photovoltaic system converters. It provides an overview of the configuration of grid-connected photovoltaic systems, different types of systems, and the classification of the converters used (DC-DC/DC-AC). The chapter then explores the structure, classification, and modeling of DC-DC converters and three-phase inverters. It discusses the principles and characteristics of Pulse Width Modulation (PWM) control, followed by the definition of Maximum Power Point Tracking (MPPT) control, various MPPT methods, and their respective characteristics. The chapter concludes by discussing the control of voltage source inverters (VSI) and the use of Phase-Locked Loop (PLL) technique for synchronization with the utility grid.

2.1 Grid-connected photovoltaic system

2.1.1 Definition

A grid-connected photovoltaic (PV) system is a solar power system that is directly connected to the electrical grid. It consists of several components that work together to convert sunlight into electricity and feed it into the grid. The main components of a grid-connected PV system are illustrated in Figure (2.1). The PV array is connected to the DC bus through a DC/DC boost converter and then to the utility grid through a DC/AC inverter [4].

2.2 Grid-connected PV system converters

As shown in Figure (II.1), two main converters are used to adapt the extracted power from the photovoltaic module and convert it to meet the requirements of the electrical grid. These converters are the DC/DC converter and the DC/AC converter.

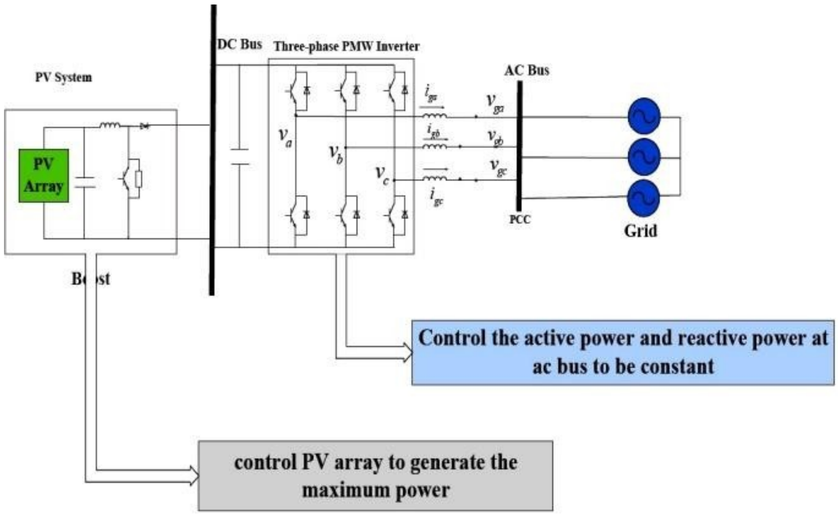

Figure 2.1: Configuration of the grid-connected photovoltaic system [4]

2.2.1 DC/DC converter

The DC-DC converter converts unregulated DC input voltage into regulated DC output voltage at a specified voltage level. Switching power supplies offer much more efficiency and power density compare to linear power supplies. Basic converters that step up or step down voltage input contains elements like transistors, diodes, capacitors and inductors.

2.2.1.1 Types of DC/DC converters

The three basic DC/DC converter topologies exist are:

Buck converter (step-down)

Boost converter (step-up)

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

2.2.1.2 Buck converter

The buck converter See Figure (2.2) is designed to step down the input voltage to a lower output voltage level. It is commonly used in various electronic devices and power systems to efficiently regulate voltage levels. The working principle of this converter can be summarized in the following steps:

1. Switching: The buck converter utilizes a power semiconductor switch, usually a transistor, to control the flow of current. The switch rapidly turns ON and OFF at a high frequency.
2. ON State: When the switch is ON, current flows from the input source through an inductor and the switch to the load. The inductor stores energy in its magnetic field and the load receives power.
3. OFF State: When the switch is turned OFF, the current path is interrupted. The inductor releases its stored energy, and the energy is transferred to the load through a diode connected in parallel with the switch. The diode prevents the current from flowing back to the input source.
4. Inductor and Capacitor: The inductor and a capacitor connected in parallel form a filtering network. The inductor smooths out the current and reduces ripple, while the capacitor filters the output voltage to provide a stable DC voltage to the load.

5. Control and Regulation: To regulate the output voltage, a feedback control mechanism is employed. It continuously monitors the output voltage and adjusts the duty cycle of the switch. The duty cycle determines the ratio of ON and OFF time of the switch, controlling the average output voltage

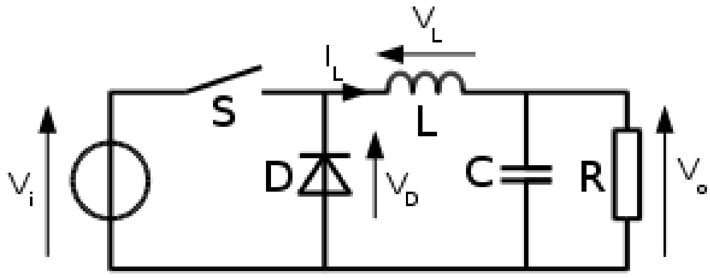

Figure 2.2: Buck converter circuit [5]

2.2.1.3 Boost converter

The boost converter (See Figure (2.3)) is used to step up or increase the input voltage to a higher output voltage. It operates based on the principle of energy storage and transfer. The working principle of a boost converter can be summarized in the following steps:

1. Energy Storage: When the switch is ON, the inductor stores energy in its magnetic field and the output capacitor charges. This causes the input voltage to be transferred and increased across the inductor.
2. Energy Transfer: When the switch is turned OFF, the inductor releases its stored energy. The stored energy flows through a diode connected in parallel with the switch, allowing the current to continue flowing in the circuit. As a result, the output voltage becomes higher than the input voltage.
3. Output Regulation: To regulate the output voltage, a feedback control mechanism is typically employed. This involves sensing the output voltage and adjusting the duty cycle of the switch to maintain the desired output voltage.

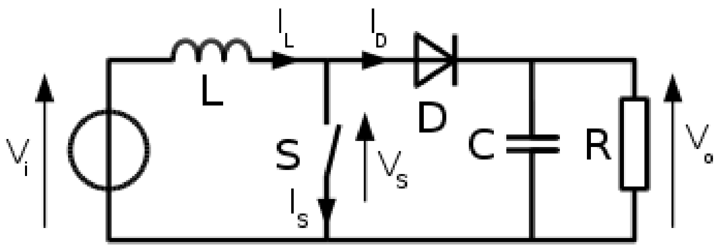

Figure 2.3: Boost converter circuit [5]

2.2.1.4 Buck boost converter

The buck-boost converter can step up or step down the input voltage to achieve a desired output voltage. It combines the functions of both a buck converter (step-down) and a boost converter (step-up)

in a single circuit. The working principle of a this converter can be summarized in the following steps:
1. Buck Mode (Step-Down): During the ON state of the switch, energy is stored in the inductor's magnetic field. The inductor current flows through the load, causing a voltage drop across it. This results in a lower output voltage than the input voltage.
2. Boost Mode (Step-Up): When the switch is turned OFF, the inductor releases its stored energy. The energy is transferred to the output through a diode connected in parallel with the switch. This causes the output voltage to be higher than the input voltage.
3. Control and Regulation: To regulate the output voltage, a feedback control mechanism is used. It monitors the output voltage and adjusts the duty cycle of the switch to maintain a stable output voltage. The duty cycle determines the ratio of ON and OFF time of the switch.

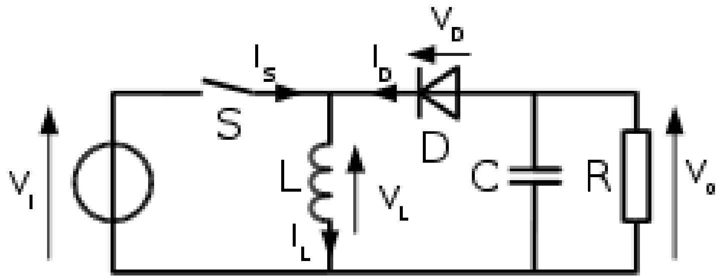

Figure 2.4: Circuit converter buck boost [5]

2.2.1.5 Modeling of boost converter

The mathematical model describing the boost converter connected to a photovoltaic generator can be written as follows [27]:

$$\begin{pmatrix} V_m \\ I_{dc} \end{pmatrix} = m. \begin{pmatrix} V_{dc} \\ I_l \end{pmatrix} \tag{2.1}$$

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

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

Where: Vm = the modulated voltage;
Idc = output current;
I-l= the inductor current;
Vpv = photovoltaic voltage;
Cpv = photovoltaic capacitance;
Ipv = photovoltaic current;
Rpv = photovoltaic resistance;
Lpv = photovoltaic inductor.

2.2.2 DC/AC CONVERTER (Inverter)

2.2.2.1 Definition

An inverter is an electronic device that converts direct current (DC) into alternating current (AC). It is commonly used in various applications, including renewable energy systems such as solar photovoltaic (PV) systems. The primary function of an inverter is to convert the DC power generated by sources like solar panels into AC power that can be used to operate electrical devices and appliances in homes, businesses, and industries. Inverters play a crucial role in enabling the integration of renewable energy sources into the existing AC power grid [28].

2.2.2.2 Classification of inverters

There are many inverters categories depending on their applications, their structures and their commands. These categories can be classified as follows [6].

2.2.2.3 Number of load phases

1. Single-Phase Inverters: Single-phase inverters produce a single-phase AC output waveform. They are commonly used in residential and small-scale commercial applications where the electrical load is relatively low. Single-phase inverters are typically used in systems with single-phase AC power supply grids.
2. Three-Phase Inverters: Three-phase inverters generate a three-phase AC output waveform. They are commonly employed in larger-scale commercial and industrial applications where the electrical load is higher.

2.2.2.4 Nature of the source

1. Current Inverter:
A current inverter, also known as a current source inverter (CSI), is an inverter that regulates the output current while allowing the voltage to vary. It converts a fixed DC current source into an AC current waveform. Current inverters are commonly used in applications such as motor drives and grid-connected renewable energy systems, where precise control of the current is required.
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.

2.2.2.5 Control mode

The control mode is classified as follows:
1. Full wave control: In full wave control, the inverter operates by switching the semiconductor devices (such as transistors or thyristors) in a full wave rectification pattern. This means that both the positive and negative half-cycles of the output waveform are controlled. Full wave control allows for the precise regulation of the output voltage and frequency but requires more complex circuitry and control algorithms.

2. Synchronous control: Synchronous control, also known as synchronous rectification, is a control mode that synchronizes the switching of the inverter's semiconductor devices with the input voltage or output waveform. By synchronizing the switching with the waveform, the inverter minimizes power losses and improves overall efficiency. Synchronous control is commonly used in high-power applications where efficiency is a critical factor.
3. Pulse Width Modulation (PWM) control: PWM control is a widely used and popular control mode for inverters. It works by modulating the width of the pulses in the inverter's switching signal. By varying the pulse width, the average value of the output voltage can be adjusted, allowing for precise control of the output waveform. PWM control offers excellent control over the output voltage, frequency, and harmonic content. It also provides high efficiency and is commonly used in various applications, including motor drives, renewable energy systems, and UPS.

2.3 Three phase inverter structure

A three-phase voltage inverter is composed of three switching arms, each consisting of two switches. Each switch is made up of either a MOSFET or an IGBT transistor that can be turned on and off, with a diode connected in anti-parallel. Figure (2.5) illustrates the block diagram of the three-phase voltage inverter [22]. In a grid-connected PV system, the inverter, also known as the DC-AC converter, converts the direct current generated by the solar modules into an alternating current that is compatible with the electrical grid. To regulate the voltages and currents at the input and output of the inverter, the switches of the inverter need to be controlled using the Sinusoidal Pulse Width Modulation (PWM) technique.

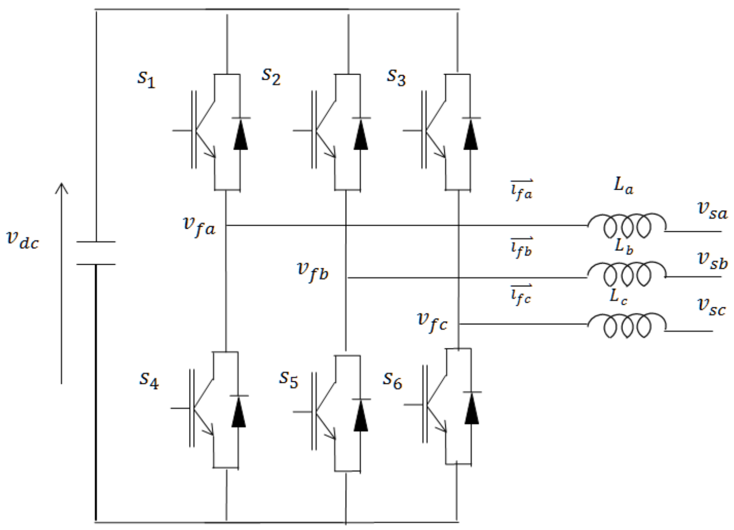

Figure 2.5: Block diagram of the three-phase inverter [6]

2.3.1 Modeling of three-phase inverter

$$V_{An} = \frac{1}{3}(V_{AB} - V_{CA}) \tag{2.4}$$

$$V_{Bn} = \frac{1}{3}(V_{BC} - V_{AB}) \tag{2.5}$$

$$V_{Cn} = \frac{1}{3}(V_{CA} - V_{CB}) \tag{2.6}$$

Where

VAO , VBo, Vco = the phase voltages of the load.

By representing the point ”o”, the voltages between phases can also be expressed as follows:

$$V_{AB} = (V_{AO} - V_{BO}) \tag{2.7}$$

$$V_{BC} = (V_{BO} - V_{CO}) \tag{2.8}$$

$$V_{CA} = (V_{CO} - V_{AO}) \tag{2.9}$$

Where

Vno = the neutral voltage of the load where

By substituting equation(2.4)(2.5)(2.6) into equation (2.7)(2.8)(2.9) the following expression is obtained :

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} V_{AO} \\ V_{BO} \\ V_{CO} \end{bmatrix} \tag{2.10}$$

Using the given relationship:

$$V_{AO} = (V_A - V_{nO}) \tag{2.11}$$

$$V_{BO} = (V_B - V_{nO}) \tag{2.12}$$

$$V_{CO} = (V_C - V_{nO}) \tag{2.13}$$

Equation (2.7) represents the mathematical model of the three-phase inverter with Pulse Width Modulation (PWM) technique:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{2.14}$$

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

The pulse width modulation technique utilizes a controller to calculate the reference voltage for the inverter (modulator) by considering the difference between the measured current and its reference value. This calculated reference voltage is then compared to a triangular signal, which acts as a high-frequency carrier setting the switching frequency. The output of this comparison, obtained from a comparator, generates the switch control command. The pulse width modulation technique is chosen for inverter control due to its outstanding performance [29].

2.4.2 Characterize the command

The PWM technique is characterized by: **1. The adjustment coefficient** The modulation adjustment coefficient, denoted as r, is defined as the ratio between the amplitude of the reference voltage modulation (Vrm) and the peak value of the carrier signal (Vpm) [30].

$$r = \frac{V_{rm}}{V_{pm}} \tag{2.15}$$

2. Modulation index The modulation index (m) is defined as the ratio between the modulation frequency and the reference frequency [31].

$$m = \frac{f_p}{f_r} \tag{2.16}$$

Where
Fp = carrier frequency.

2.4.3 Modeling of pulse width modulation

The modeling of the Sinusoidal Pulse Width Modulation (PWM) command can be represented by the following equations:
Reference equation: The three sinusoidal reference voltages are given by

$$\begin{bmatrix} V_{A_{ref}} = V_{rm}\sin 2\pi f_r t \\ V_{B_{ref}} = V_{rm}\sin 2\pi f_r t \\ V_{C_{ref}} = V_{rm}\sin 2\pi f_r t \end{bmatrix} \tag{2.17}$$

Carrier equation: The triangular carrier equation is expressed by

$$V_p(t) = V_{mp}[\frac{1}{2} - \frac{sin(cos(2pF_p(t)))}{pi}] \tag{2.18}$$

The figure shown in Figure(2.6) represents a timing diagram generated by a three-phase sine-triangle PWM command.

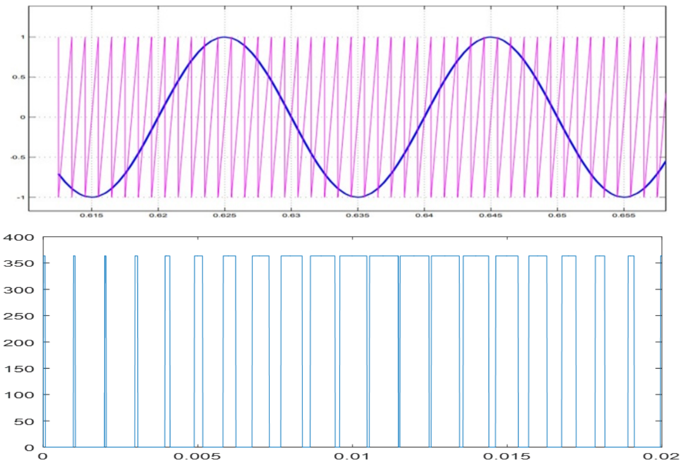

Figure 2.6: Diagram delivered by an PWM command

2.5 Maximum POWER POINT Tracking(MPPT)

2.5.1 Principle

In order to ensure that a solar power system operates at its maximum power points, specific control laws are implemented. This type of control is commonly referred to as "Maximum Power Point Tracking" (MPPT) in the English literature. The underlying principle of these control techniques is to locate the maximum power point (MPP) while achieving optimal matching between the generator and its load for efficient power transfer. Figure (1.8) illustrates a basic photovoltaic conversion chain integrated with MPPT control. The MPPT control is connected to a static converter that facilitates the adaptation between the solar power generator and the load, ensuring the generated power is maximized and directly transferred to the load [32]. A grid-connected photovoltaic (PV) system is a solar power system that is directly connected to the electrical grid. It consists of several components that work together to convert sunlight into electricity and feed it into the grid. The main components of a grid-connected PV system are illustrated in Figure(2.1.) The PV array is connected to the DC bus through a DC/DC boost converter and then to the utility grid through a DC/AC inverter [4].

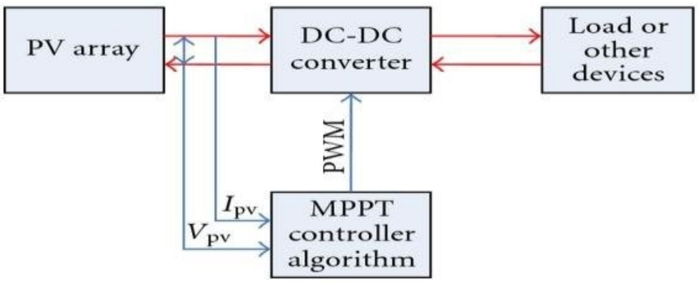

Figure 2.7: Diagram delivered by an PWM command [7]

2.5.1.1 Direct methods

Direct determination methods of MPPT rely on general operating point characteristics and utilize current and voltage measurements. Among these techniques, the most commonly used method is known as "Perturb and Observe". This method involves manipulating the duty cycle to adjust the operating point of the solar power generator [33].

2.6 MPPT techniques

Various techniques are employed for tracking the maximum power point (MPP). Some of the most popular techniques include:

- 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 is a simple approach for maximum power point tracking. It involves using a single sensor, typically a voltage sensor, to measure the voltage of the solar cell array. This results in lower implementation costs and easier implementation. The time complexity of the P& O algorithm is generally low. However, as it approaches the maximum power point (MPP), it may overshoot and continue to perturb in both directions. To address this, an appropriate error limit can be set or a waiting function can be employed to increase the algorithm's time complexity. These modifications help ensure that the algorithm operates in the vicinity of the MPP [34].

2.6.2 Incremental Conductance

Among the MPPT techniques described in the literature that have proven to be efficient in tracking the maximum power points, one notable technique is the Perturb and Observe algorithm (P and O). The P and O algorithm, also known as Cond Inc, is particularly effective when the solar cell field is subjected to rapid changes in climatic conditions. This algorithm operates based on the derivative of the panel's output power with respect to its voltage, enabling it to dynamically adjust the operating point and maximize power extraction [34].

2.6.3 Fractional open circuit voltage

The Fractional Open Circuit Voltage method, belonging to the second category mentioned above, has been extensively studied in recent research. This method utilizes the approximate linear relationship between the open-circuit voltage (Voc) and the voltage at the maximum power point (Vmpp). By analyzing this relationship, the Fractional Open Circuit Voltage method enables effective tracking of the maximum power point for optimal power extraction [31].

2.6.4 Fractional short circuit current

FSCC (Fractional Short Circuit Current) technique is a straightforward and efficient method for tracking the maximum power point of a photovoltaic system. To track the power, this technique relies on obtaining the value of the short circuit current (Isc) by temporarily isolating the PV array. The FSCC method can be implemented using either analog or digital approaches. The fundamental principle behind this technique is that the current at the maximum power point (Impp) is typically in close proximity to the short circuit current (Isc). By utilizing this relationship, the FSCC technique achieves accurate and rapid MPPT [31].

2.6.5 Fuzzy Logic Control

The utilization of fuzzy logic control has gained popularity in Maximum Power Point Tracking (MPPT) systems, particularly in microcontroller-based controllers, over the last decade. Fuzzy logic controllers offer several advantages such as the ability to work with imprecise signals, not necessitating a precise mathematical model, and effectively handling nonlinearity. These characteristics make fuzzy logic controllers well-suited for MPPT applications where environmental conditions and system parameters can vary, enabling efficient and robust tracking of the maximum power point.

Table 2.1: Characteristics of different MPPT technique

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

2.7 Characteristics of different MPPT techniques

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

2.8 Perturb & Observe Algorithm(P&O)

The Perturb and Observe (P & O) method is based on monitoring the power output of the solar cell array and introducing small variations in power by adjusting the voltage or current of the array. This technique involves applying a slight perturbation to the system, which results in a change in the power output of the solar module. If the power increases as a result of the perturbation, the perturbation continues in that direction. Once the peak power is reached, the power output starts to decrease, and the perturbation is reversed. As the system approaches a steady state, the method oscillates around the peak power point. To ensure minimal power variation, the size of the perturbation is kept very small. Figure(2.8) illustrates the principle of the Perturb and Observe (P & O) method [9]:

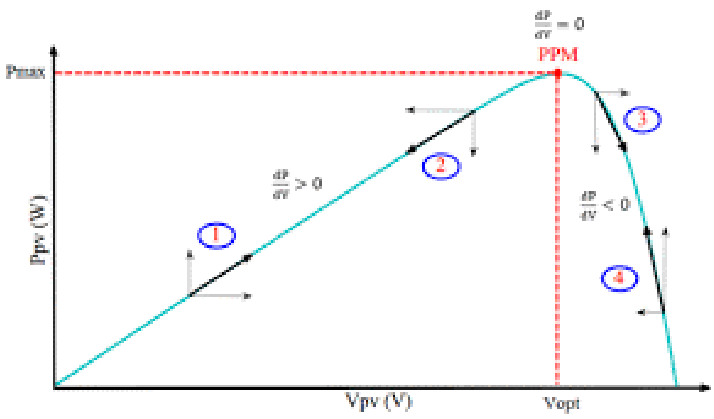

Figure 2.8: Principle of P&O method [8]

The Perturb & Observe (P & O) method, as mentioned earlier, offers simplicity and ease of implementation. However, this method has limitations that reduce its efficiency in accurately tracking the maximum power point (MPP). One drawback is the decreased effectiveness of the P&O method in locating the MPP as the solar irradiation level decreases. The power-voltage (P-V) curve becomes less distinct, making it challenging for the MPPT system to accurately determine the MPP due to minimal power changes compared to voltage perturbations. Another drawback is the inability of the P&O method to determine when it has reached the actual MPP. Instead, it continuously oscillates around the MPP, changing the perturbation direction after each power measurement.

To overcome these limitations, modifications and enhancements have been made to the MPPT algorithm in solar PV systems. The proposed modified Perturb and Observe algorithm demonstrates a faster response in mismatching conditions, quicker convergence to the MPP, and higher accuracy in accurately tracking the actual MPP. These modifications improve the overall performance of the MPPT system, ensuring optimal power extraction from the solar PV system.

The algorithm for this control method is depicted in Figure (2.9), and its principle revolves around generating disturbances by adjusting the duty cycle D and observing the corresponding effect on the power received from the solar power generator: - If the rate of change of electrical power with respect to voltage (dpv / dVpv) is greater than θ, indicating an increase in voltage, the duty cycle is increased as well. This is achieved through the equation D(k) = D(k-1) + δD, where δD is a constant used for increment. - If the rate of change of electrical power with respect to voltage (dpv / dVpv) is less than θ, implying a decrease in voltage, the duty cycle is decreased. This is achieved through the equation D(k) = D(k-1) − δD. By continuously adjusting the duty cycle based on the observed changes in power, this control method seeks to track and converge towards the maximum power point of the solar power generator.

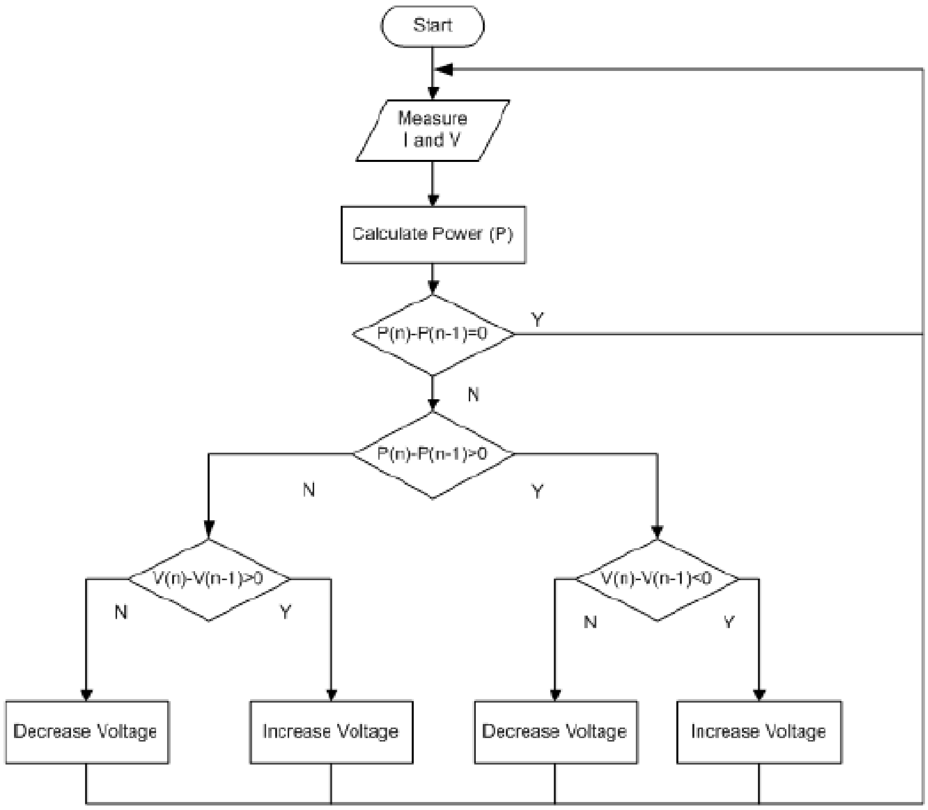

Figure 2.9: Flowchart of the Perturb and observe algorithm [9]

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 converts a unidirectional voltage waveform into a bidirectional voltage waveform. It serves as a converter, transforming the voltage from DC form to AC form. In an ideal scenario, a Voltage source Inverter maintains a constant voltage throughout the conversion process. The voltage waveform eabc and the output current waveform iabc, obtained from the grid connection point, can be expressed as follows after the abc/dq0 conversion [11]. The typical model for current control in the inner control loop is as follows:

$$I_d = (K_p + \frac{K_i}{S})(P_{ref} - P_{cal}) \tag{2.19}$$

$$I_q = (K_p + \frac{K_i}{S})(Q_{ref} - Q_{cal}) \tag{2.20}$$

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

$$U_d = (K_p + \frac{K_i}{S})(I_{d_{ref}} - P_{d_{cal}}) \tag{2.21}$$

$$U_q = (K_p + \frac{K_i}{S})(I_{q_{ref}} - I_{q_{cal}}) \tag{2.22}$$

2.9.2 Active & reactive power control (P & Q)

The purpose of this type of control is to regulate the active and reactive power injected into the grid. The control circuit is responsible for adjusting the currents in such a way that the current supplied by the inverter is smooth and in phase with the corresponding phase-to-neutral voltage. The detailed schematic diagram below illustrates this control, and its principle is presented in the following figure (2.10).

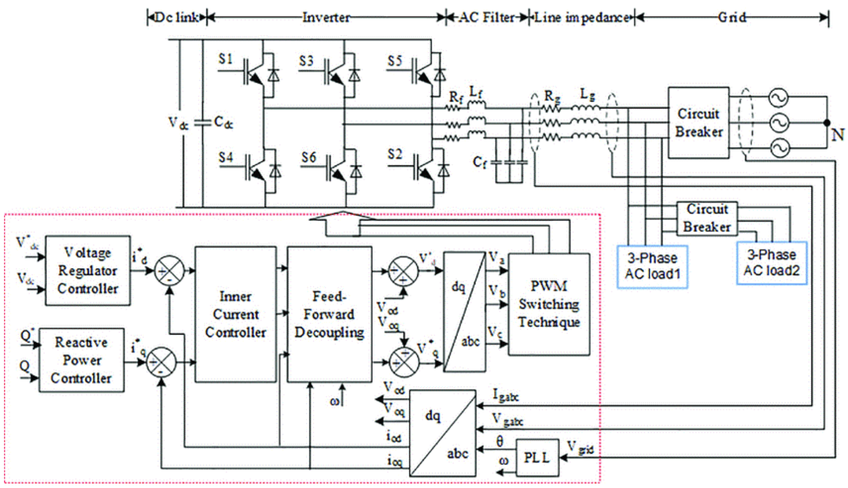

Figure 2.10: Synoptic diagram Grid-connected PV system with three-phase inverter control [10]

The system analysis and subsequent simplifications have led us to the conclusion that the reference currents at the output of the upstream control will be injected at the point of PV production connection. These currents are calculated based on power references and voltage measurements at the connection point. They are then computed in the Park transformation according to the following equations:

$$P_{ref} = (V_{dr} I_{dref} + V_{qr} I_{qref}) \tag{2.23}$$

$$Q_{ref} = (V_{dr} I_{dref} + V_{qr} I_{qref}) \tag{2.24}$$

$$I_{d_{ref}} = \frac{(V_{dr} P_{ref} + V_{qr} Q_{ref})}{(V_{qr} + V_{qr})^2} \tag{2.25}$$

$$I_{q_{ref}} = \frac{(V_{dr} P_{ref} + V_{qr} Q_{ref})}{(V_{qr} + V_{qr})^2} \tag{2.26}$$

Where:

. Pref and Qref= are the reference powers of the PV production

- Vdr and Vqr= are the direct and quadrature components of the voltage, measured at the point of connection of PV production, in the Park transformation.

- Idr-ref and Iqr-ref= are the reference direct and quadrature components of the current produced by the PV production and injected into the connected network.

To calculate the currents, the measured voltage is converted to the Park reference system. A Phase-Locked Loop (PLL) is utilized to synchronize the Park transformation with the measured voltage pulse on the network.

2.9.3 Control of the DC bus voltage

Controlling the DC bus is a fundamental process in the system. By monitoring the voltage fluctuations at the capacitor terminals, we can gain insights into the energy exchange dynamics between the capacitors and the network. The time evolution of the voltage at the terminals can be obtained by integrating the capacitive current.

$$I_C = I_{pv} - I_{ond}) \tag{2.27}$$

and

$$V_{dc} = \frac{1}{C} \int (I_{pv} - I_{ond}) dt \tag{2.28}$$

Where

Ic = capacitor current,

Iond = inverter courant

Vdc =dc voltage, Cdc is dc capacitor.

By regulating the power transmitted through the system, it is possible to control the energy stored in the capacitor and thereby regulate the DC bus voltage. The control loop implemented for this purpose is depicted in the following Figure(2.11).

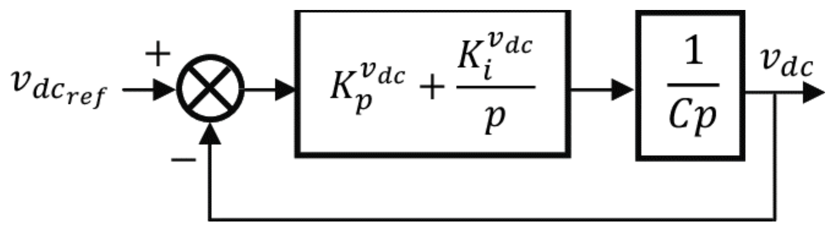

Figure 2.11: Diagram DC bus voltage regulation loop

2.10 Phase locked loop (PLL)

The phase-locked loop (PLL) provides precise frequency information that is utilized to compensate for these distortions. The standard block diagram of a single-phase PLL comprises three components: the Phase Detector (PD), the Loop Filter (LF), and the Voltage Controlled Oscillator (VCO). These components work together to generate an output signal that can track the input signal accurately [35].

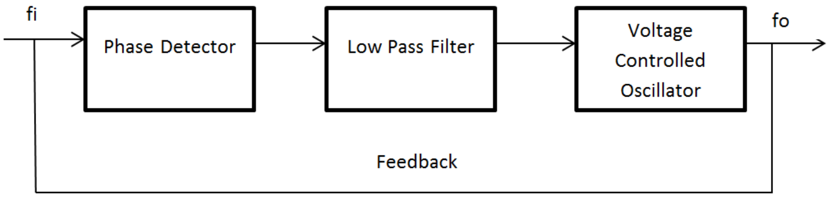

Figure 2.12: Block diagram PLL [11]

2.10.1 Phase detector

Phase detectors used within a PLL can be either digital or analog. Monolithic PLL circuits typically employ analog phase detectors, while discrete PLL implementations use digital phase detectors. The primary role of the phase detector in a PLL is to function as a comparator circuit. It compares the frequencies of the input signal and the VCO output, generating a DC voltage based on their phase difference [36].

2.10.1.1 Low Pass Filter

To eliminate high-frequency components and noise, a low-pass filter is employed in the PLL. The low-pass filter plays a crucial role in controlling various characteristics of the PLL, such as bandwidth, transient response, and capture and lock ranges.

2.10.1.2 Voltage controlled oscillator

The Voltage Controlled Oscillator (VCO) in a PLL circuit is responsible for generating an output frequency that is directly proportional to the input frequency.

2.10.2 Synchronization

The philosophy of the Park PLL is illustrated in this diagram. In this PLL, the phase angle is detected by synchronizing the rotating reference frame of the PLL with the utility voltage vector. By setting the reference voltage Vrd* to zero on the direct axis, the PLL locks onto the phase angle of the utility voltage vector. The output of the PI controller is the inverter output frequency, which is then integrated to obtain the inverter phase angle θ. additionally, the instantaneous frequency and amplitude of the voltage vector are also determined. When the difference between the grid phase angle θr and the inverter phase angle θ ond is reduced to zero ($\delta\ \theta = \theta$), the PLL becomes active and we obtain [37] :

$$V_{rd} = 0 and V_{rq} = -\sqrt{3}V_r \tag{2.29}$$

To determine the parameters of the PI controller, the equivalent linear models shown in the Figure (2.13) are used. These models represent the dynamics of the system and provide a basis for controller design [38].

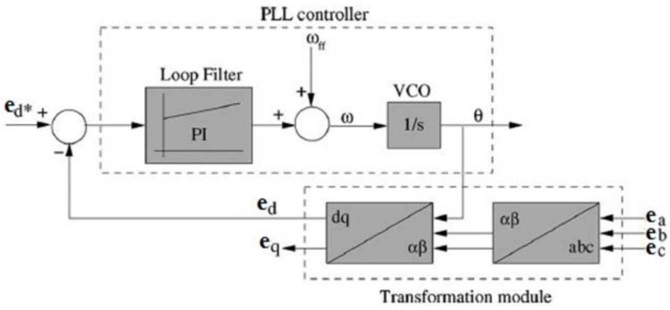

Figure 2.13: Structure of a PLL system for grid synchronization [12]

Conclusion

In these two chapters, we have discussed the control of a grid-connected photovoltaic system converter. We first introduced the grid-connected photovoltaic generation system and defined the DC/DC converter. We discussed the structure and types of chopper, followed by the operating principle and modeling of the boost converter. We also defined and classified the DC/AC converter, and discussed the structure and modeling of the three-phase inverter. We explored the principle and characteristics of pulse width modulation (PWM), as well as the various methods and techniques of maximum power point tracking (MPPT). We specifically explained the Perturb & Observe algorithm and its principle and algorithm. Finally, we studied the control of the Voltage Source Inverter (VSI) and the synchronization using the phase-locked loop(PLL).

In the next chapter, we will focus on the simulation and results of the system

CHAPTER 3

SIMULATION AND RESULTS OF THE PROPOSED GRID-CONNECTED PV SYSTEM

Introduction

This chapter focuses on the simulation and presentation of the results for the proposed grid-connected PV system. The simulation is performed using the PSIM platform, which allows us to simulate various components of the system, including the PV generator, the boost converter, and the voltage source inverter. The results obtained from each individual component will be presented and discussed separately. Furthermore, the entire system will be simulated under varying irradiance conditions, and the corresponding results will be presented and analyzed comprehensively.

3.1 Proposed photovoltaic system

The schematic block diagram of the proposed PV grid-connected system in this study is illustrated in Figure (3.1.) It comprises a photovoltaic generator connected to a boost converter, responsible for tracking the maximum power point. Subsequently, there is a voltage source inverter (VSI) that is connected to the DC bus (output of the boost converter) on one side, and to the point of common coupling through an L filter on the other side. The VSI is controlled to maintain a fixed DC bus voltage, ensuring the stability of its output voltage. The synchronization of the VSI output voltage with the utility grid is achieved through a phase-locked loop (PLL) control strategy. This ensures the proper alignment and synchronization between the VSI and the utility grid voltage.

3.2 Characteristics of the used PV panel

Before proceeding with the simulation of the various components of the proposed system, it is important to provide an overview of the characteristics of the PV panel that has been utilized to construct the PV generator. The table below illustrates the physical and electrical characteristics of the employed PV panel under Standard Test Conditions (STC) (G=1000 W/m^2, 25°C).

To plot the I-V and P-V characteristics of the PV panel being used, its output is connected to a capacitor C. Subsequently, the current flowing through the capacitor (Ipv) and the voltage across the

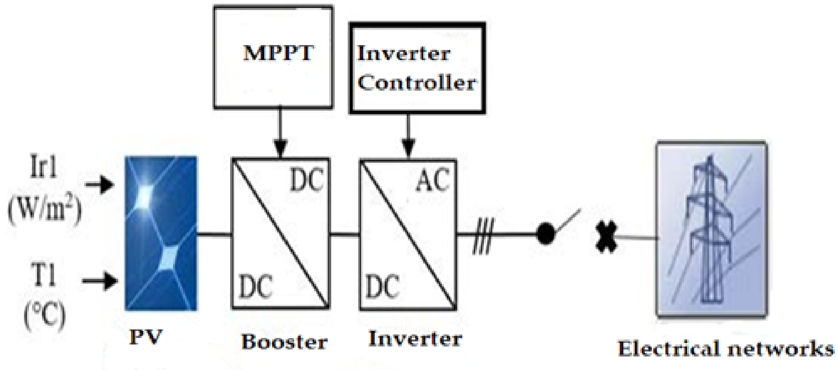

Figure 3.1: Schematic diagram of a photovoltaic system connected to the grid

Table 3.1: Physical and electrical characteristics of the panel

Elecrical and Electrical characteristic	Value
Number of cells (Ns)	72
Short circuit current (Isc)	8.77
Open circuit voltage (Vco)	44.6
Maximum power (Pmax)	317.72
Maximum power voltage (Vmp)	38.88
Maximum power current (Imp)	8.17

capacitor (Vpv) are measured and multiplied to obtain the panel power (Ppv), as illustrated in Figure (3.2):

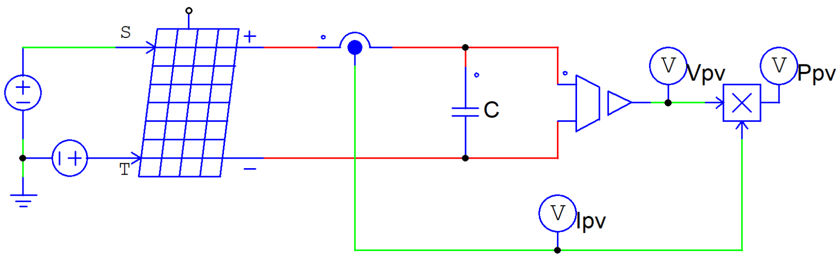

Figure 3.2: I-V and P-V plotting characteristic circuit of the PV panel

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 PV panel, a PV generator has been designed by assembling the previous panel in parallel/series configuration. However, since the PSIM platform does not have the capability to design a PV generator solely by specifying the parallel/series numbers of the panels and requires physical connections between them, this increases the calculation time and slows down the simulation execution. Therefore, we chose to develop our PV generator based on the characteristics of the previous panel, with the ability to indicate only the number of parallel/series panels, as shown in the

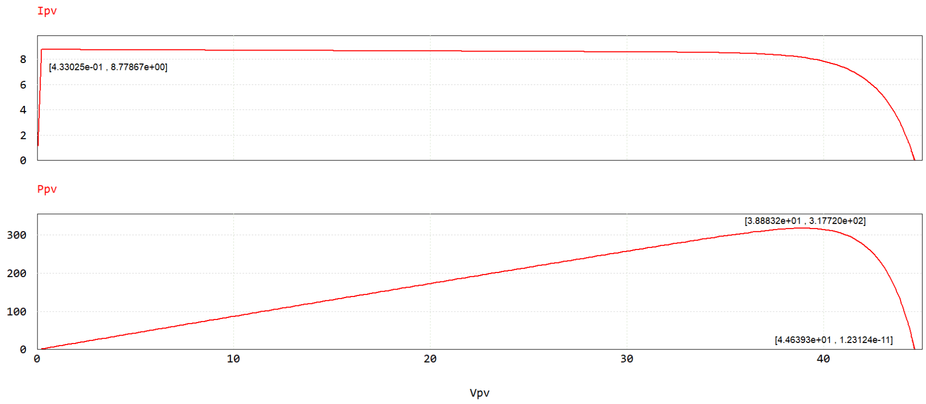

Figure 3.3: I-V and P-V characteristics of the panel

Table 3.2: Physical and electrical characteristics of the PV generator.

Elecrical characteristic	value
Number of panel 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

figure below. The table below summarizes the characteristics of the PV generator used.

The same principle used in the PV panel is applied to plot the I-V and P-V curves of the PV generator.

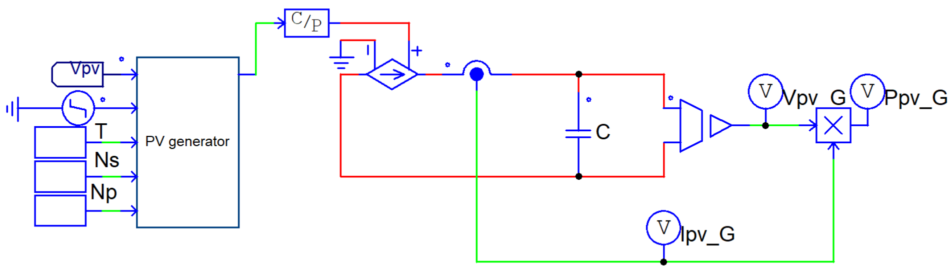

Figure 3.4: I-V and P-V plotting characteristic circuit of the PV generator

The I-V and P-V curves of the previous PV generator under two different irradiation values of 1000/500 W/m2 and a temperature of 25° are presented in Figure (3.5) and Figure (3.6) respectively. The obtained results confirm the electrical characteristics under the STC conditions given in Table(3.2)

3.4 Boost converter

Before proceeding with the simulation, the initial step involves determining the parameters of the boost converter. The sizing of this converter, which is used to track the maximum power point, differs from

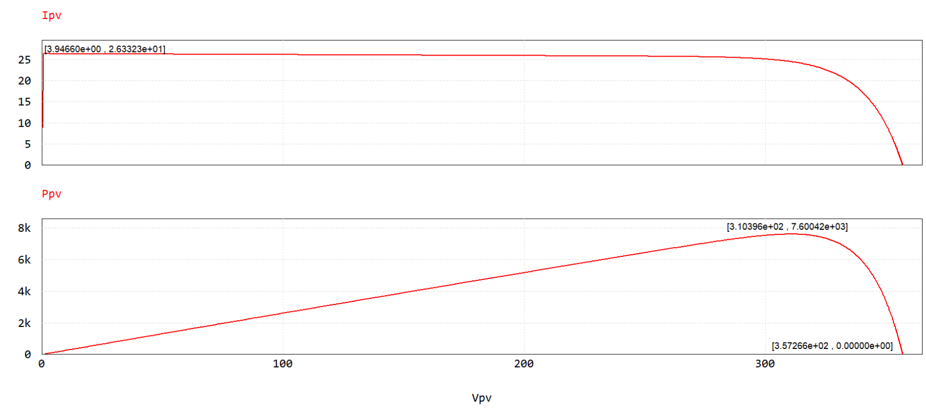

Figure 3.5: -V and P-V characteristics of the pv generator under 1000W/m2, 25°

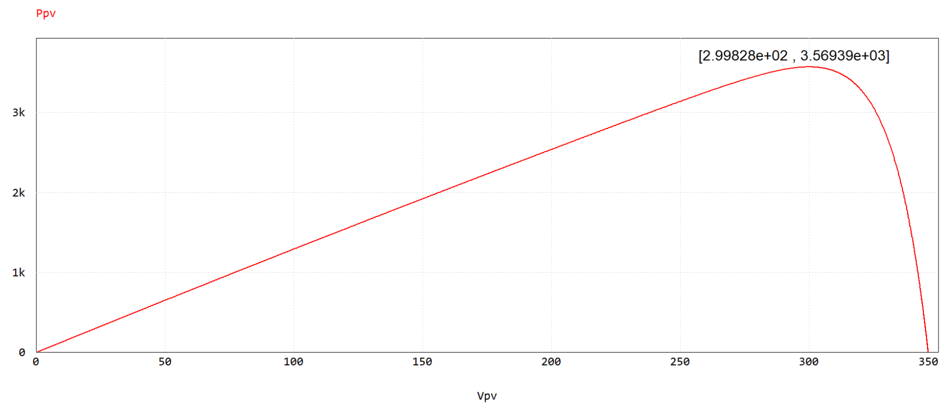

Figure 3.6: P-V Characteristic of the PV generator under 500W/m2, 25°

the classical converter where its input is typically fixed. The boost converter utilized in this study consists of an input capacitor CI, an inductor L, and an output capacitor CO. The values of these three parameters are calculated using the following three equations:
Inductor (L):

$$L = \frac{V_{mp} D_{mp}}{2dIF_s} \tag{3.1}$$

Where
V-mp = themaximum power voltage,
D-mp = D of maximum power,
dI= the current ripple
F-s = the switching frequency;

Input capacity (C-I):

$$C_I = \frac{4V_{mp} D_{mp}}{dV_I R_I F_s} \tag{3.2}$$

Where

Table 3.3: Parameters of the boost converters

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

RI = input resistance,

dV-I = ripple voltage.

Output capacity (C-o):

$$C_o = \frac{2V_O D_{mp}}{dV_{V_o} R_o F_s} \tag{3.3}$$

Where

V0 = output voltage,

dV-0 = ripple voltage,

R0 = output resistance.

The parameters of the boost converter are calculated based on equations(3.1)(3.2)(3.3.) The obtained parameters are listed in Table (3.3)

3.5 PV generator maximum power point tracking

Maximum Power Point Tracking algorithms are utilized to determine the optimal output efficiency of a photovoltaic system. Ensuring that the PV array consistently operates near this MPP holds the potential for achieving the highest efficiency. To maintain our PV generator's performance at its best potential, it is connected to the boost converter, which has been sized in the previous sections. The boost converter plays a crucial role in tracking the MPP using the previously explained P&O algorithm. Figure (3.7) provides a detailed depiction of the first part of the system, where the P&O algorithm has been implemented in a PSIM C block.

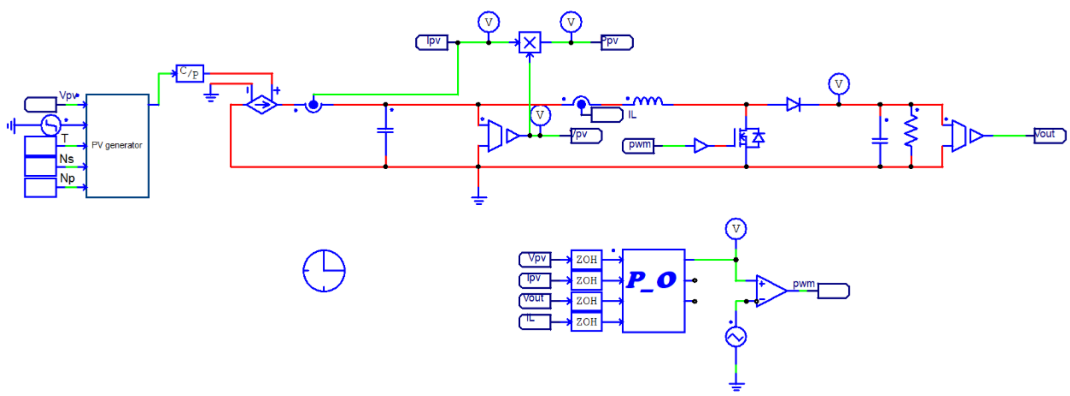

Figure 3.7: PV generator with boost converter controlled by P&O algorithm

From Figure (3.8), it can be observed that at the 2.5s point, the irradiance shifts from 1000 to 500

W/m2. According to Figure (3.5), and Figure (3.6) the MPPT points for these respective irradiance levels are 7.6 kW and 3.57 kW. It is found that the output power of the PV generator is 7.58 kW and 3.565 kW, confirming the achievement of MPP for both irradiations with an error of 0.003% and 0.001% respectively. This behavior demonstrates the effectiveness of the MPPT control in tracking and maintaining the PV system's operation at the maximum power point. These results validate the high efficiency of the circuit sizing and the P&O algorithm.

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

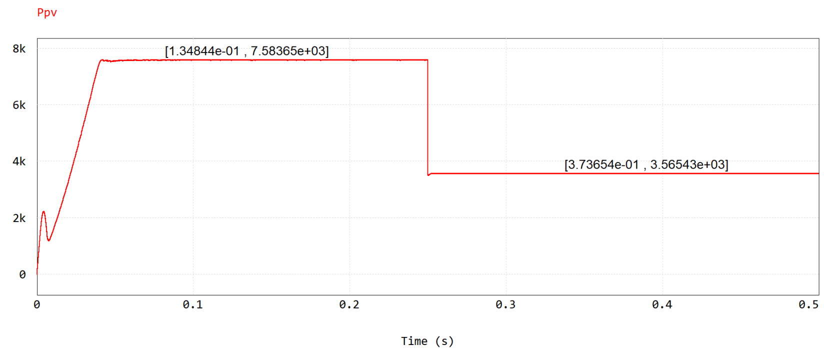

Figure 3.8: PV generator output power

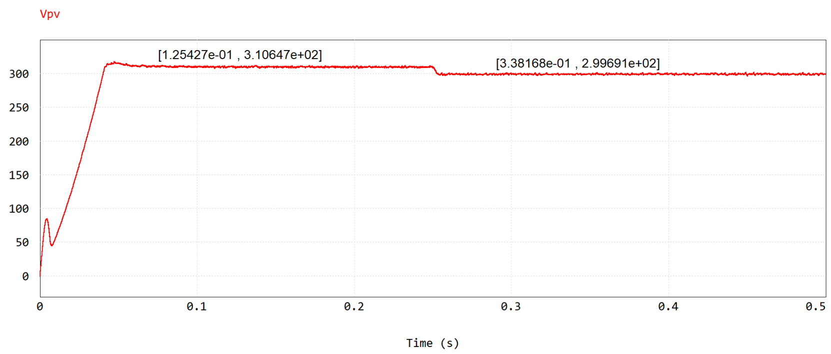

Figure 3.9: PV generator output voltage (Vpv)

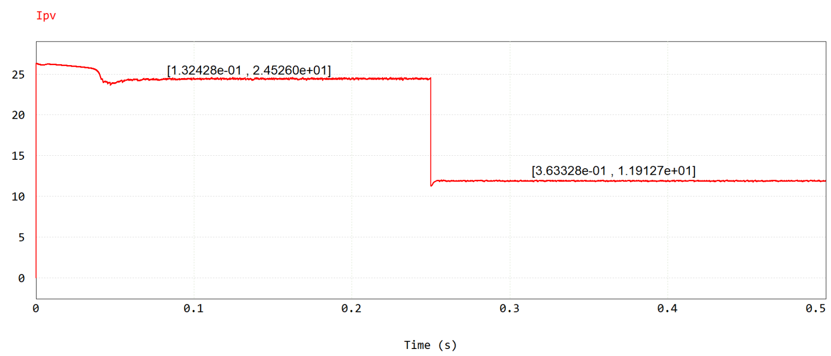

Figure 3.10: PV generator output current (Ipv)

3.6 Grid injected active and reactive power control

In a grid-connected PV system, the primary objective is to transfer all the available power extracted from the PV generator to the grid. The Voltage Source Inverter (VSI) controller plays a crucial role in generating the appropriate gate signals for the IGBT switches within the inverter, facilitating the generation of the required AC voltages, currents, and power. Therefore, before initiating control over the DC bus voltage, the DC bus is replaced by a DC voltage source in order to commence by the control of active and reactive grid-injected power. Figure (3.11)illustrates the electrical components of the circuit, including the C block that encompasses the control software.

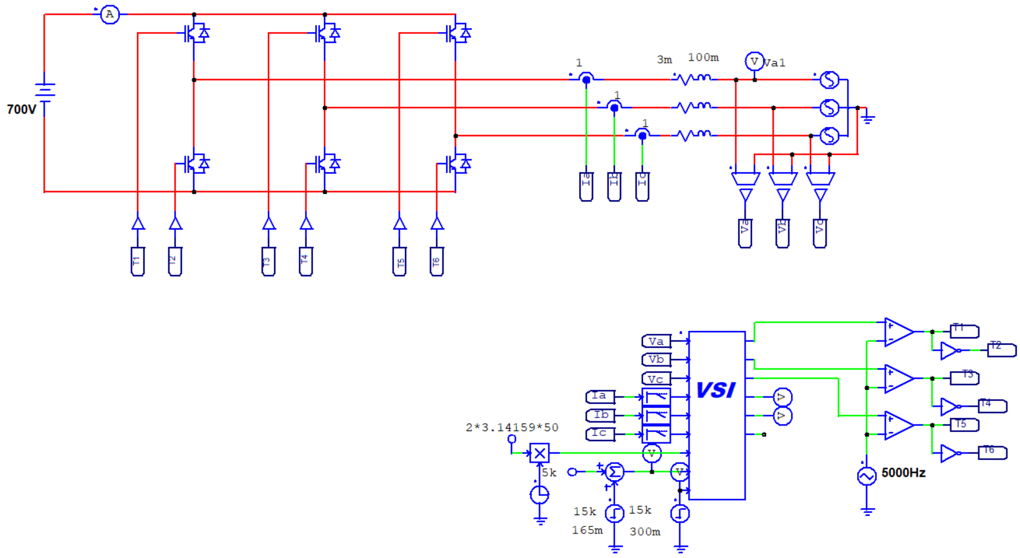

Figure 3.11: Active and reactive grid-injected power control circuit

Figure (3.12) and Figure(3.13)illustrate the injected active and reactive power along with their corresponding references. Both figures show how the power curves superpose their reference signals. With the exception of small instances when the reference signals shift from one value to another, the power curves transition from their steady state to a transition phase and then quickly reach their steady state again.

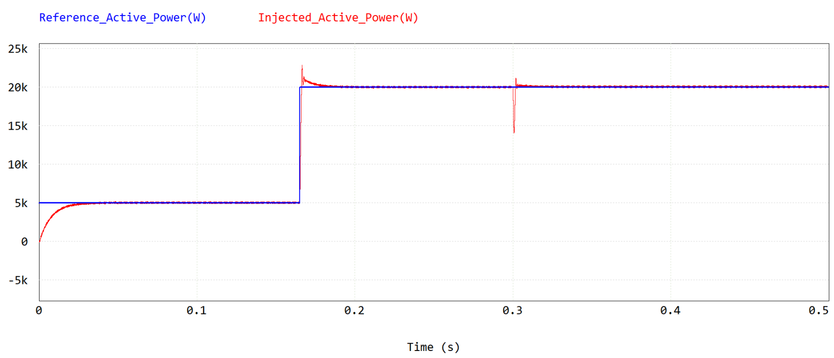

Figure 3.12: Injected active power and its reference.

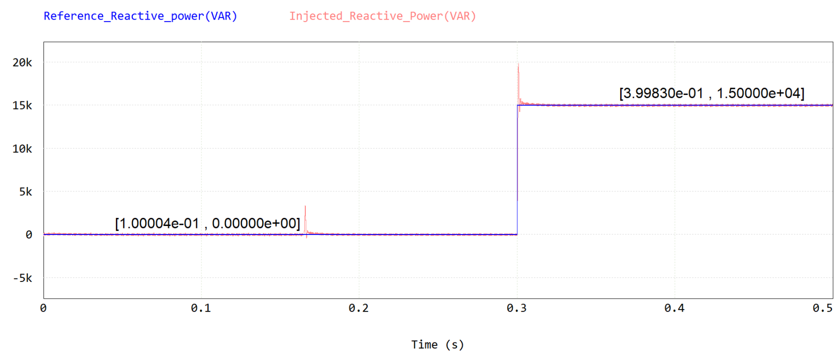

Figure 3.13: Injected reactive power and its reference

3.7 DC bus voltage control

In the proposed topology of the grid-connected PV system, it is essential to maintain a constant DC bus voltage despite the variable current flowing into the DC bus capacitor. To achieve this, the output of the boost converter is replaced by a controlled current source before connecting it to the DC bus. This controlled current source injects a variable current into the DC bus capacitor. Figure (3.14) displays the electrical circuit with the C block containing the control software, while Figure(3.11)illustrates the injected current

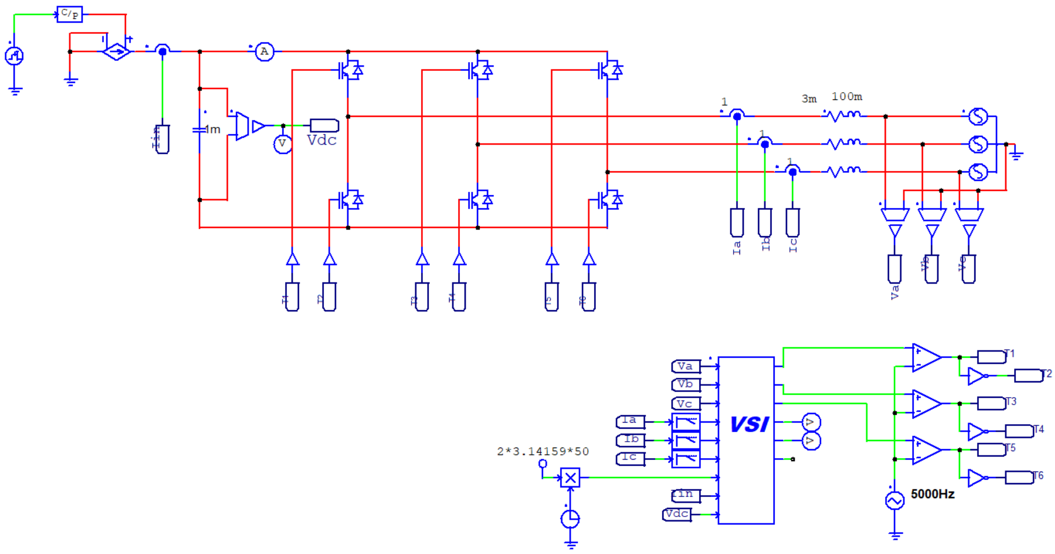

Figure 3.14: schema of DC bus voltage

Figure (3.16)illustrates that the DC bus voltage is maintained at the reference voltage of 700V, with a negligible error of 1V.

3.8 Photovoltaic grid-connected system control

After independently simulating the two parts of the proposed grid-connected PV system, which include the boost converter responsible for efficiently increasing the voltage from the photovoltaic generator and ensuring the PV generator operates at its optimal operating point using the P&O algorithm, and the

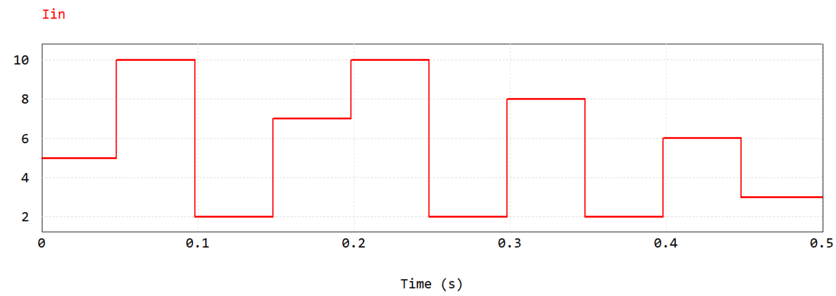

Figure 3.15: Injected current to the DC bus

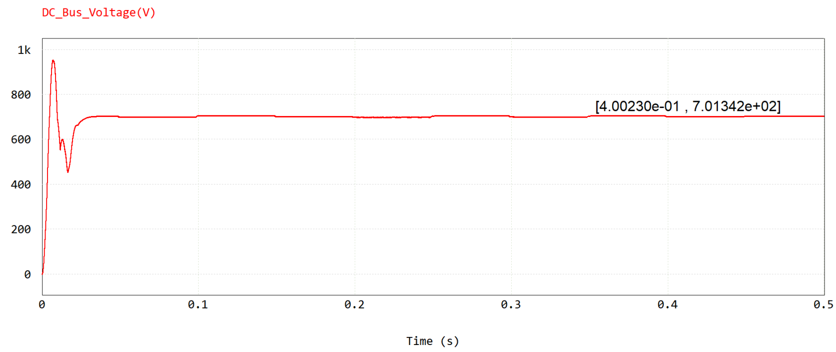

Figure 3.16: DC bus voltage

voltage source inverter used to convert DC power into AC power while controlling the injected active power to maintain a constant DC bus voltage through decoupled control, connecting both parts allows the transfer of maximum power supplied from the PV panel to the utility grid with optimal efficiency. The electrical circuit with C blacks containing the software the control algorithms are illustrated in Figure (3.17)

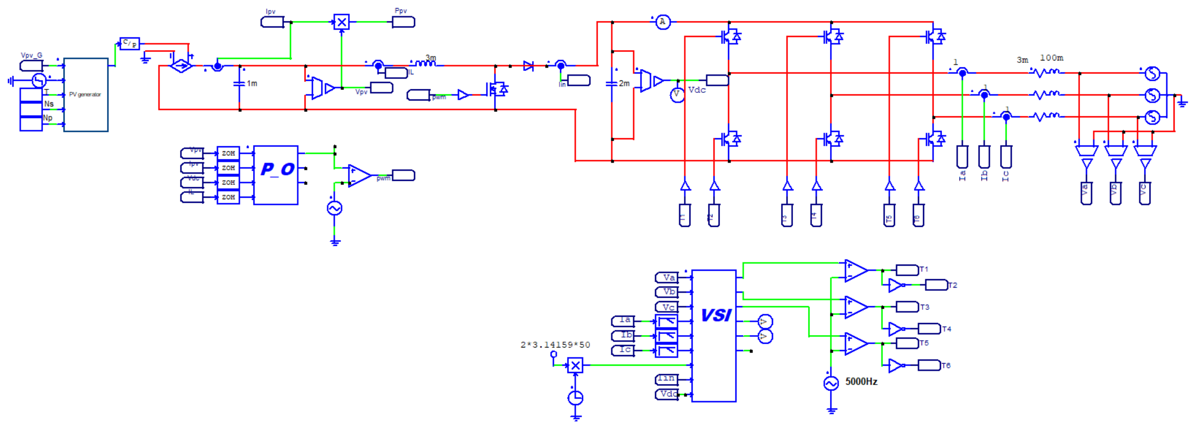

Figure 3.17: Grid-connected PV system circuit

3.8.1 Obtained simulation results

The system depicted in Figure(3.17) is simulated in the PSIM platform under two irradiation values of 1000 / 500 W/m2, with each value maintained for a duration of 2.5 seconds, starting with the highest value. The obtained results after the simulation of the system for 5 second are illustrated in the figures below. Figure (3.18) illustrates the extracted power from the PV generator, which corresponds to the maximum power that can be delivered under the two irradiation values. Figure (3.19) and Figure

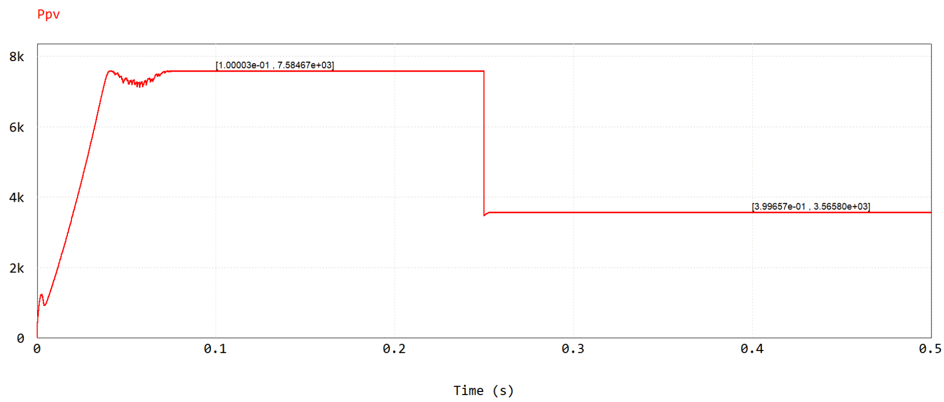

Figure 3.18: PV generator delivered power

(3.20) illustrate the active injected power and reactive power, respectively. The active injected power corresponds to the power extracted from the PV generator, as shown in Figure (3.8), with only minor shifts due to IGBT transitions. However, the reactive power is zero since the PV generator only delivers active energy.

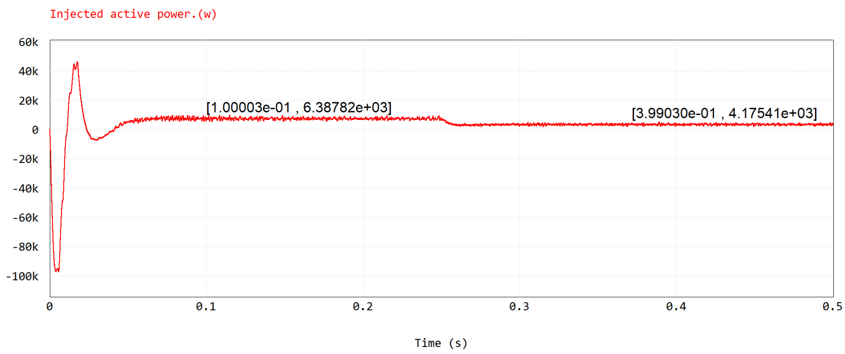

Figure 3.19: Injected active power.

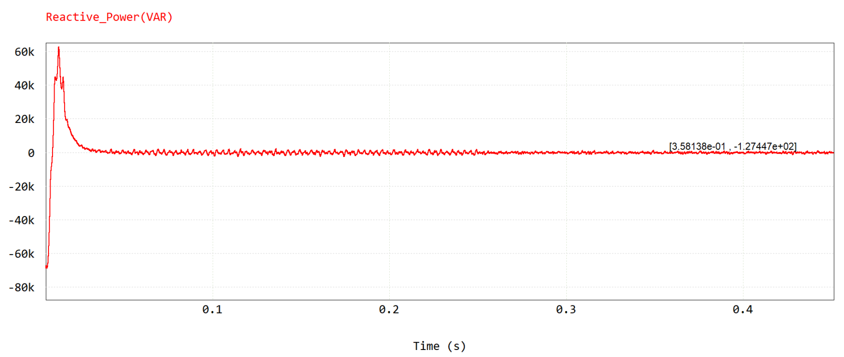

Figure 3.20: Reactive power

Figure (3.21) shows the DC bus voltage maintained at reference voltage of 700V with an error of

2V, regardless of the shifting in PV generator output current that occurred at the instant 2.5-second, as depicted in Figure (3.8)

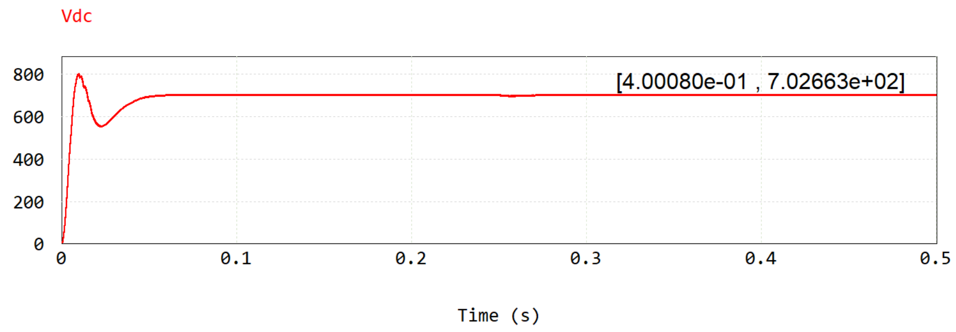

Figure 3.21: DC bus voltage.

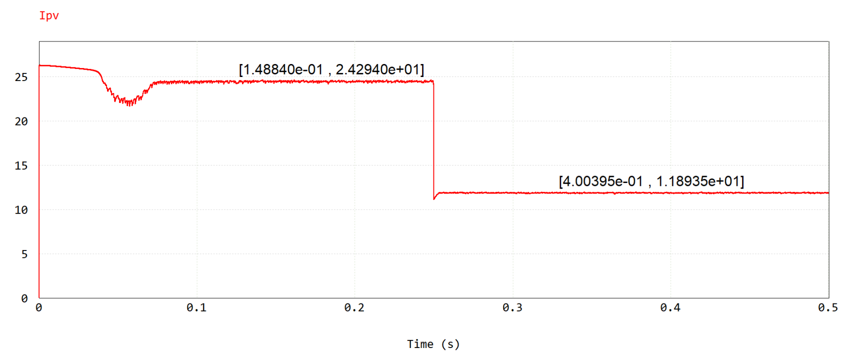

Figure 3.22: PV generator output current.

Figure (3.23) depicts the three-phase current injected into the grid. The currents are almost sinusoidal and reflect the values of the extracted current from the PV generator presented in Figure (3.22)

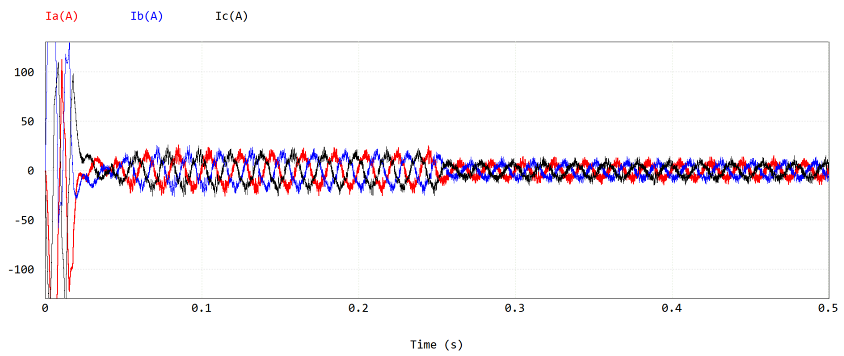

Figure 3.23: Grid injected current.

Conclusion

In this chapter, simulations were conducted in the PSIM platform, and results were obtained for the grid-connected PV system. The primary focus was on simulating each part of the system independently. First, the implementation of a maximum power point tracking method was simulated to extract the maximum power from the PV generator. Then, the second part of the system, which focused on controlling the injected active and reactive power along with the control of the DC bus voltage, was also simulated. The second part of this chapter was dedicated to simulating the entire system. Two different irradiance values were utilized, the extracted power was aligned with the maximum power point of the PV generator. Subsequently, this power was successfully injected into the main grid.

GENERAL CONCLUSION

The work presented in this thesis focuses on the modeling and control of a grid-connected photovoltaic system. This system is expected to undergo significant developments mainly driven by a growing commitment to diversify the means of electrical energy production and transition towards renewable energy sources. To simplify the understanding of this work, this thesis has been presented in three chapters. The second chapter was devoted to the control of converters in a grid-connected photovoltaic system. An overview of the grid-connected PV system was provided. The definition of the DC-DC converter was discussed, and different types of DC-DC converters were explored. The principle and modeling of the boost converter were presented, and the definition and classification of the inverter were described. The three-phase inverter was examined, and the modeling of the inverter and the principle of pulse width modulation (PWM) were discussed, along with various methods and techniques of maximum power point tracking (MPPT). The focus was on the perturb and observe algorithm. The chapter concluded by discussing the control of the inverter using voltage source inverter (VSI) and phase-locked loop (PLL) control. At the end of this work, the grid-connected photovoltaic system was simulated and controlled using the PSIM software platform. Each part of the system was individually simulated, and the obtained results were discussed. Subsequently, the entire system was simulated to assess its overall performance. The results obtained from the simulations confirmed the effectiveness of the proposed grid-connected PV system in successfully injecting the maximum extracted power into the main grid.

SUMMARY

In this work, the modeling and control of the grid-connected photovoltaic system were presented. The study incorporates a comprehensive representation of the key components in the system, including the photovoltaic array, boost converter, and grid-connected inverter. Effective control strategies were developed for the DC/DC converter to optimize the extraction of power from the photovoltaic generator. The inverter facilitates the smooth transfer of the generated power to the grid while maintaining a constant DC bus voltage. The simulation results obtained using the PSIM software validate the performance of the control methods for grid-connected photovoltaic systems.

Key words: PV – Boost converter – Inverter – Grid – MPPT – VSI.

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