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Three Phase Grid Connected Inverter based on Sliding Mode Controller for PV System

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بسم الله الرحمن الرحيم

ABSTRACT

This dissertation presents a control strategy based on Sliding Mode Control (SMC) for a grid-connected photovoltaic (PV) system. The approach addresses key challenges such as system nonlinearities, parameter uncertainties, environmental disturbances, and variability due to changing weather conditions. The proposed system architecture includes a DC-DC boost converter employing (P&O) algorithm for Maximum Power Point Tracking (MPPT), and a DC-AC inverter responsible for DC-link voltage regulation, grid power injection, and unity power factor operation. The effectiveness and robustness of the control strategies are validated through complete simulation results.

Keywords: Sliding Mode Control (SMC), Maximum Power Point Tracking (MPPT), Boost Converter, PV System, Perturb and Observe (P&O), DC-Link Voltage Control, Grid-Connected Inverter.

ملخص:

تقترح هذه الدراسة استخدام التحكم بالانزلاق (Sliding Mode Control - SMC) لإدارة نظام شمسي متصل بالشبكة الكهربائية، بهدف التغلب على التحديات المرتبطة بالطبيعة غير الخطية، والتغيرات المناخية، والاضطرابات الخارجية، والتقلبات في الإشعاع الشمسي. تتضمن استراتيجية التحكم المقترحة استخدام محولين: محول رافع (Boost Converter) على جانب المولد الشمسي لتنفيذ تقنية تتبع نقطة القدرة العظمى (MPPT) باستخدام خوارزمية الاضطراب والمراقبة(P&O) ، ومحول آخر على جانب الشبكة لتنظيم حقن الطاقة، والحفاظ على استقرار جهد ناقل التيار المستمر(Vdc) ، وتحقيق معامل قدرة يساوي واحد. تم التحقق من كفاءة هذه الاستراتيجية من خلال نتائج المحاكاة.

الكلمات المفتاحية :تتبع نقطة القدرة العظمى، محول رافع، النظام الكهروضوئي، خوارزمية الاضطراب والمراقبة، التحكم في ناقل التيار المستمر، التحكم بالانزلاق.

DEDICATION

I dedicate this study from the bottom of my heart to our dear parents, who have been our source of inspiration and strength when we considered giving up, and who have continually provided us with their moral, spiritual, emotional, and financial support. Also, I dedicate this study to our brothers, sisters, relatives, mentors, friends, and classmates who shared their advice and encouragement for completed this study.

THANKS, AND APPRECIATION

I would like to thanks my parents, my family, my teachers and many close friends. To the two persons that gave me the tools and values necessary to be where I am standing today. I will never finish to thank my father and my mother for all the opportunities they have offered me. For all the teachings that they have told me and for every piece of advice that has come out of their mouth. I am so grateful to them for trusting me that I would do a Good job at the university.

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V_s : supply voltage (input)

R1 : resistor

R2 : load resistor (voltage at its terminal is output voltage)

DZ : Zener diode

Q : transistor

V : voltage (V)

I : current (A)

I_{ph} : Photocurrent, a function of irradiance and cell temperature (typically 5 A)

I0 : Reverse saturation current of the diode (0.0002 A)

R_s : Series resistance of the PV cell (0.001 Ω)

T_c : Operating temperature of the cell (20 °C)

k : Boltzmann constant (1.38×10−23J/^{0}K)

e : Electron charge (1.602×10−19C)

INTRODUCTION

In recent decades, the increasing global demand for clean and sustainable energy has accelerated the development and deployment of renewable energy systems. Among these, solar energy has emerged as a leading candidate due to its abundance, environmental friendliness, and technological advancements. Photovoltaic (PV) systems, which convert solar radiation directly into electricity have gained significant attention in residential, commercial, and industrial sectors.

Despite their promising nature, PV systems face multiple challenges that limit their efficiency. These include the non-linear behavior of solar panels, dependency on weather conditions, and fluctuations in solar irradiance and temperature. As a result, the output power of PV modules is highly variable, and continuously adapting the operating point to track the maximum power point (MPP) becomes essential.

To overcome these limitations, various MPPT algorithms have been developed. The Perturbation and Observation (P&O) and Incremental Conductance (IC) methods are among the most widely used due to their simplicity and effectiveness. In recent years however, more robust control techniques have been introduced and integrated with MPPT methods such as fuzzy logic control, in order to enhance energy conversion efficiency and increase the overall performance of PV systems.

In this context, the present work investigates the application of advanced control strategies for MPPT in grid-connected PV systems. The study begins by presenting a comprehensive overview of PV system components and operation principles. It then explores and compares classical MPPT techniques such as P&O with IC. Additionally, introduces a Sliding Mode Control (SMC) approach as robust control method for grid-connected PV.

This thesis is structured into three main chapters:

- Chapter 1 introduces general concepts related to solar energy, solar radiation, photovoltaic technologies, and focuses on the modeling of a photovoltaic system including the PV generator.
- Chapter 2 discusses DC-DC converters and examines the working principles of MPPT techniques, along with a theoretical study and comparison of selected methods.
- Chapter 3 presents the modeling and simulation of a grid-connected PV system using a sliding mode controller. It aims to demonstrate how SMC can improve the dynamic response and overall efficiency of power conversion under variable environmental conditions of a grid-connected PV system.

Finally, the thesis concludes with a general conclusion and future perspectives related to the development of intelligent and robust control systems for renewable energy applications.

CHAPTER 1: Overview of Photovoltaic Systems

1.1. Introduction

The global shift toward renewable energy sources has significantly increased the adoption of photovoltaic (PV) systems as a sustainable solution for electricity generation. These systems efficiently convert solar energy into electrical energy using solar cells and can be deployed in both standalone and grid-connected configurations.

Grid-connected PV systems, in particular, have gained increasing importance due to their ability to support public utility networks and reduce reliance on conventional energy sources. However, these systems face several technical challenges, most notably the continuous variation in operating conditions such as solar irradiance and temperature, which directly affect their efficiency.

To overcome these limitations, MPPT techniques are employed to extract the maximum available power from PV panels at all times. Among the various MPPT algorithms, the Perturb and Observe (P&O) method is widely used due to its simplicity and ease of implementation.

In addition to MPPT, efficient power flow regulation to the grid requires a robust control structure involving both DC-DC and DC-AC converters. Given the inherent nonlinearity and parameter uncertainties of PV systems, advanced control strategies like SMC become essential to ensure stable performance and reliable maximum power tracking.

This chapter provides a technical overview of photovoltaic systems and their components laying the foundation for the control challenges addressed in the subsequent chapters of this thesis.

1.2. Renewable Energy System

1.2.1. Definition of Renewable Energy

Renewable energy can be defined as energy derived from natural resources that are inexhaustible and are constantly renewed. Renewable energy is also known as energy resulting from natural sources that are renewed at a rate greater than what is consumed. Renewable energy is also called by several terms, including clean energy and environmentally friendly energy. The uses of renewable energy are concentrated in generating electrical energy, while other uses such as heating and cooling water as well as use in transportation are still not sufficiently exploited.[1]

significantly reduces greenhouse gas emissions that contribute to rising global temperatures.

reduces local air pollution and water contamination.

- provides energy security by developing local sources that are flexible and can respond to community needs.

- improves local economy by creating jobs and placing value on lands that supply renewable energy sources. [2]

1.2.2. The importance of energy in the modern world:

Renewable energy is one of the most sustainable solutions that can help achieve the world's goals in tackling climate change and reducing carbon emissions. It offers alternatives to fossil fuels, which cause air and water pollution and contribute to global warming. [3]

1.3. Solar energy

Photovoltaic solar energy is the most competitive and the fastest-growing and most widely installed energy source in the world. This clean energy boasts remarkable environmental, economic, and social benefits, aligning its advantages with sustainable development goals. But despite its strengths, it is not without its challenges. These limitations, while surmountable, merit careful consideration, especially for those considering investing in this sector.

1.3.1. Historical Evolution of PV Technology

The development of photovoltaic (PV) technology spans more than a century, with significant milestones marking its evolution. The first practical photovoltaic cell was developed in 1954 by researchers at Bell Telephone Laboratories. This silicon-based solar cell had an efficiency of approximately 6% and marked the beginning of PV technology as a viable energy source.

During the late 1950s and 1960s, PV cells found their first major application in space technology, where they were used to power U.S. satellites. Their reliability and ability to generate power in isolated environments made them ideal for space missions.

In the late 1970s, photovoltaic systems began to be deployed in remote and off-grid areas on Earth—locations without access to conventional electricity infrastructure. These early terrestrial applications proved the utility of PV technology in diverse environments.

A major shift occurred after 2004, with the widespread adoption of grid-connected PV systems. These systems, installed on rooftops, buildings, and large-scale solar farms, feed electricity directly into the power grid. The expansion of PV deployment was driven by technological advancements, reductions in production and installation costs, and favorable policy measures such as tax incentives and net metering programs.

By the mid-1990s and continuing to the present day, the number of installed PV systems has increased exponentially. In countries like the United States, millions of grid-connected systems are now operational, contributing significantly to national energy portfolios.

This historical development reflects not only the technological maturation of photovoltaic systems but also their growing role in global efforts toward sustainable and renewable energy.[4]

1.4. Solar radiation

Solar radiation is radiant (electromagnetic) energy from the sun. It provides light and heat for the Earth and energy for photosynthesis. This radiant energy is necessary for the metabolism of the environment and its inhabitants. The three relevant bands, or ranges, along the solar radiation spectrum are ultraviolet, visible (PAR), and infrared. Of the light that reaches Earth's surface, infrared radiation makes up 49.4% of while visible light provides 42.3%. Ultraviolet radiation makes up just over 8% of the total solar radiation. Each of these bands has a different impact on the environment. [5]

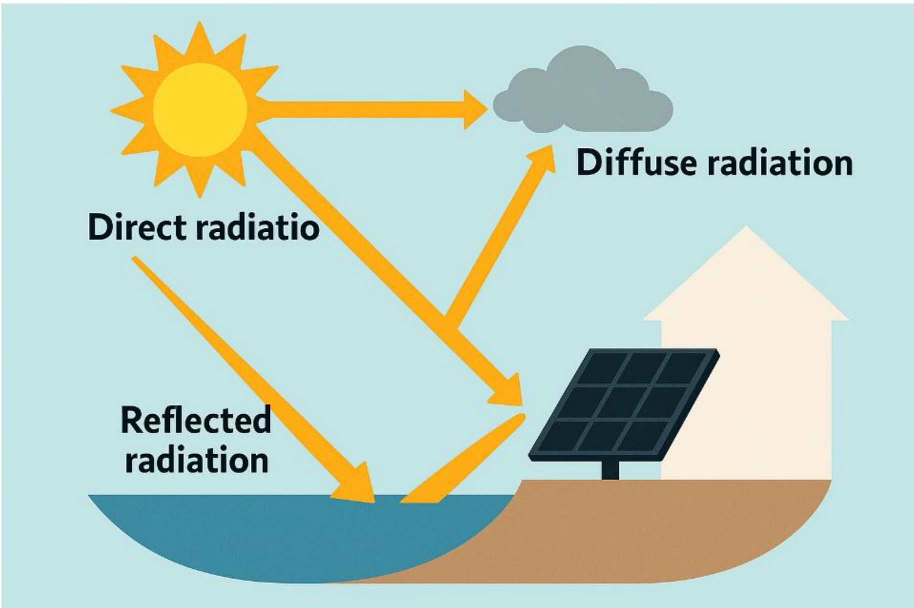

Figure 1.1: Types of Solar Radiation Affecting Solar Panels.

1.4.1. Direct radiation

This type of radiation penetrates the atmosphere and reaches the Earth's surface without dispersing at all on the way.

1.4.2. Diffuse radiation

This is the radiation that reaches the Earth's surface after having undergone multiple deviations in its trajectory, for example by gases in the atmosphere.

1.4.3. Reflected radiation or ground albedo

This is the fraction of solar radiation that is reflected by the earth's surface itself, in a phenomenon known as the albedo effect. [6]

1.4.4. Global radiation

it is the radiation, received on a horizontal surface, coming from the Sun and the entire celestial vault; it is measured with a pyranometer. [7]

is the sum of these various radiations. It reaches a value of 1000 W/m² on a clear, cloudless day. This radiation can be measured using a pyranometer or a solarimeter. Most of the time, solar energy is determined by cumulative radiation.

To do this, daily global radiation is calculated; this is the integral of global radiation over a day at a given location with a given inclination (usually horizontal). The cumulative radiation is measured in Wh/m² per day. This data is accumulated from year to year, and averages for each month of the year are thus determined. These values are available with the PVGIS (Photovoltaic Geographical Information System) information system. [8]

1.5. Solar panels

1.5.1. Definition

Solar panels are devices that convert sunlight into electricity through the photovoltaic (PV) effect. Their efficiency, performance, and applications depend on various factors, including the technology used, environmental conditions, and installation method.

1.5.2. The PV cell

Photovoltaic (PV) cells, commonly known as solar cells, are devices that convert sunlight directly into electricity through a process called photovoltaics. These cells are constructed from semiconductor materials that absorb photons, freeing electrons and generating an electric current. The photovoltaic effect was first noted by French physicist Alexandre-Edmond Becquerel in 1839, and significant advancements have been made sense then, including the development of the first silicon solar cell in 1954, which marked a turning point in solar technology. [9]

The photovoltaic cell (also known as a photoelectric cell) is a device that converts sunlight into electricity through the photovoltaic effect, a phenomenon discovered in 1839 by the French physicist Alexandre-Edmond Becquerel. Over the years, other scientists, such as Charles Fritts and Albert Einstein, contributed to perfecting the efficiency of these cells, until reaching the current silicon ones, whose use has become increasingly more accessible and efficient. [10]

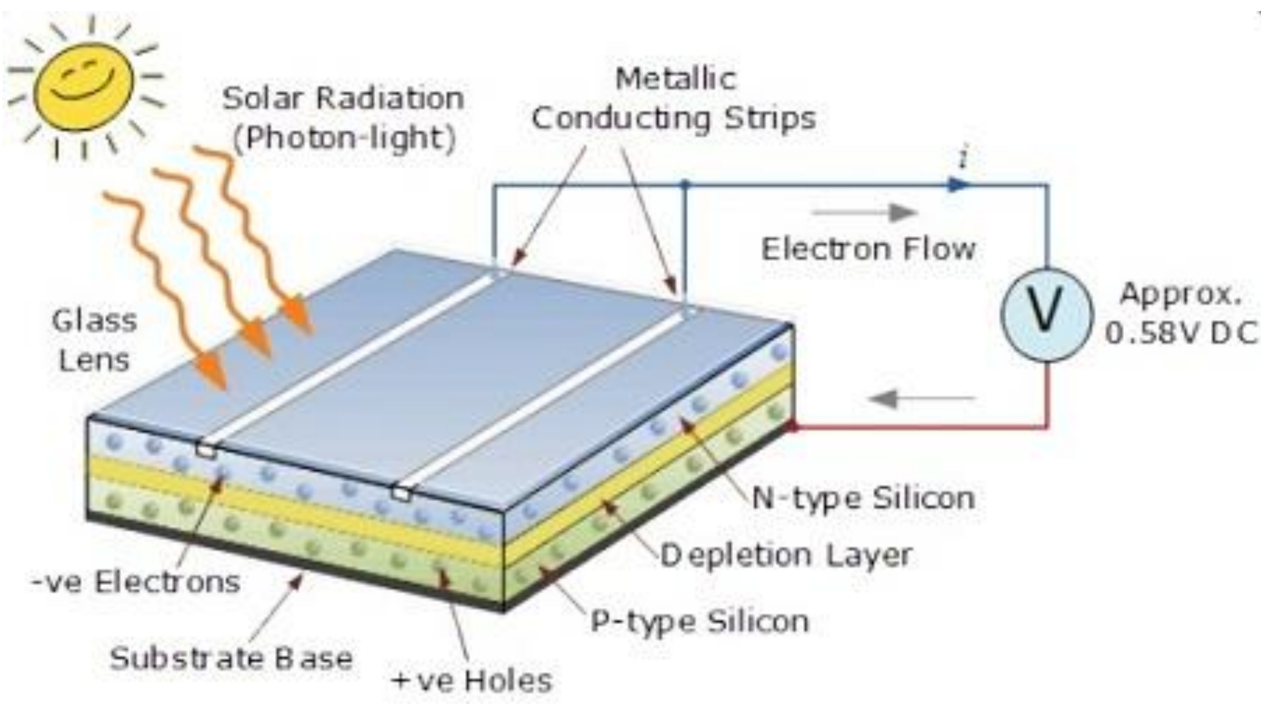

Figure 1.2: Model showing a PV cell.

1.6. Type and performance of photovoltaic cells

1.6.1. Monocrystalline Silicon Cell

The most effective of the solar PV cells with 15% efficiency, monocrystalline silicon is therefore the more expensive option. They require less space than other cells simply because they produce more energy and can yield up to four times more power than thin-film solar panels. They also last longer than other panels and perform better at low light.

The main disadvantage is the cost which often means that it's not the first choice for home owners. It can also be affected by dirt or shade, which can break the circuit and the production process is often seen as wasteful because the cells have to be cut into wafers.

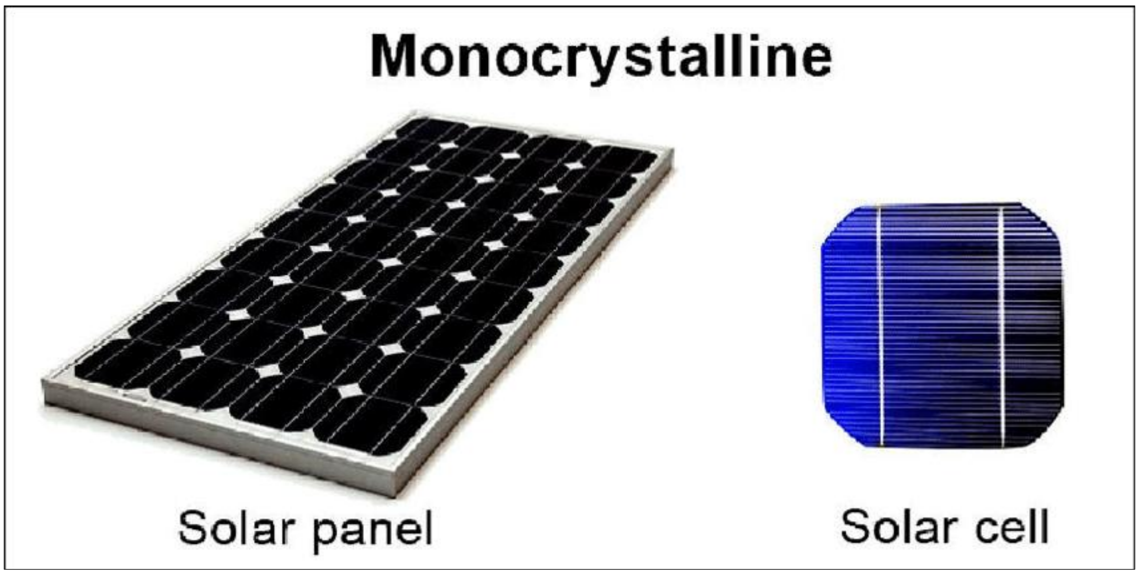

Figure 1.3: Monocrystalline Silicon Cell.

1.6.2. Polycrystalline Silicon Cell

With an efficiency of 13%, polycrystalline solar panels are often seen as a better economic choice, particularly for home owners. They are made from a number of smaller silicon crystals that are melted together and then recrystallized. The process to create them is simpler and less wasteful than with monocrystalline panels. They do suffer more at high heats that can reduce their lifespan but overall perform just as well as their more expensive counterpart.

The main disadvantage for polycrystalline solar panels is that you need more of them because of the lower energy conversion efficiency.

1.6.3. Amorphous/thin film Cell

At 7%, thin film solar panels are among the least efficient on the market but they are the cheapest option. They work well in low light, even moonlight, and are made from non-crystalline silicone that can be transferred in a thin film onto another material such as glass. The main advantage is that it can be mass produced at a much cheaper cost but is more suitable for situations where space is not a big issue.

The main disadvantage for thin film solar panels are not generally used for residential purposes and will degrade quicker than crystalline cells.

1.6.4. Hybrid silicon cell

With an efficiency of 18%, hybrid soler panels are made from a mix of amorphous and monocrystalline cells to generate maximum efficiency. There are a variety of types of hybrid cells and they are still very much at the research and development stage which is why they are currently a more expensive option. [11]

1.7. Types of Photovoltaic Systems

PV systems can be categorized based on their connection to the electric grid, their use of energy storage, and their integration with other power sources. The main types are:

1.7.1. Grid-Connected (Grid-Tied) PV System

- Connected directly to the utility grid.
- Solar panels generate electricity, which is either used on-site or fed back into the grid.
- Do not require batteries, as the grid acts as a backup when solar production is insufficient.
- Common for Operate independently from the utility grid.
- Rely on batteries to store excess energy for use at night or during cloudy periods.
- Often used in remote locations where grid access is unavailable.
- May be designed residential, commercial, and utility-scale installations.

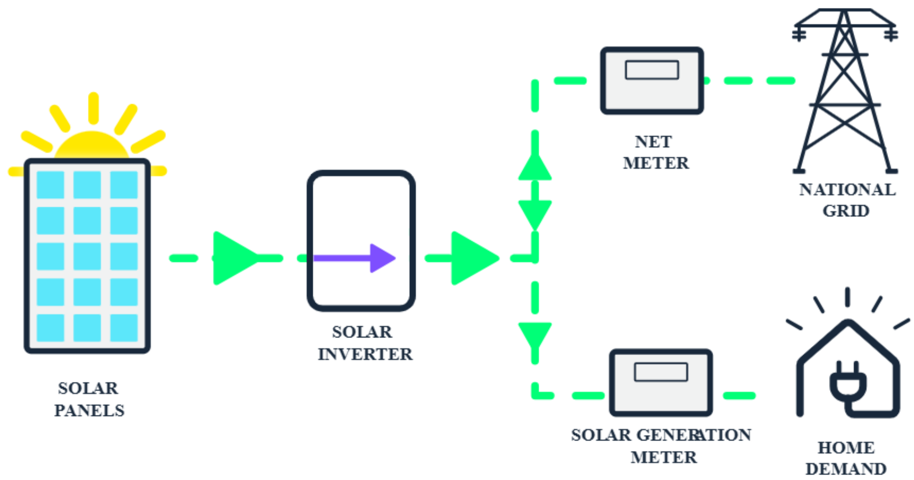

Figure 1.4: On-Grid Solar System.

1.7.2. Stand-Alone (Off-Grid) PV System

- as DC-only systems (for direct loads) or include inverters for AC loads.

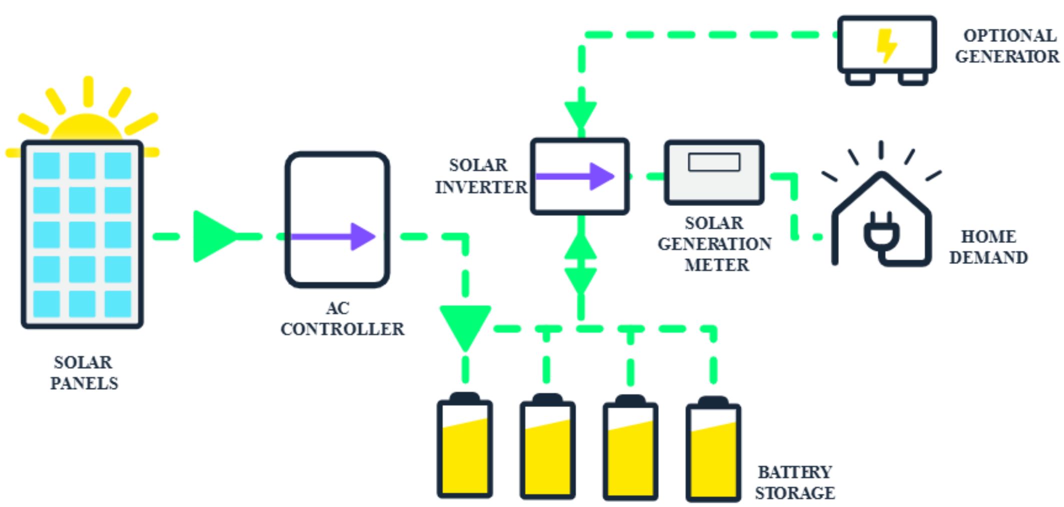

Figure 1.5: Off-Grid Solar System.

1.7.3. Hybrid PV Systems

- Combine solar PV with other energy sources, such as diesel generators, wind turbines, or the grid.
- Include batteries for energy storage, enhancing reliability and flexibility.
- Useful in areas with unreliable grid access or where continuous power supply is critical.

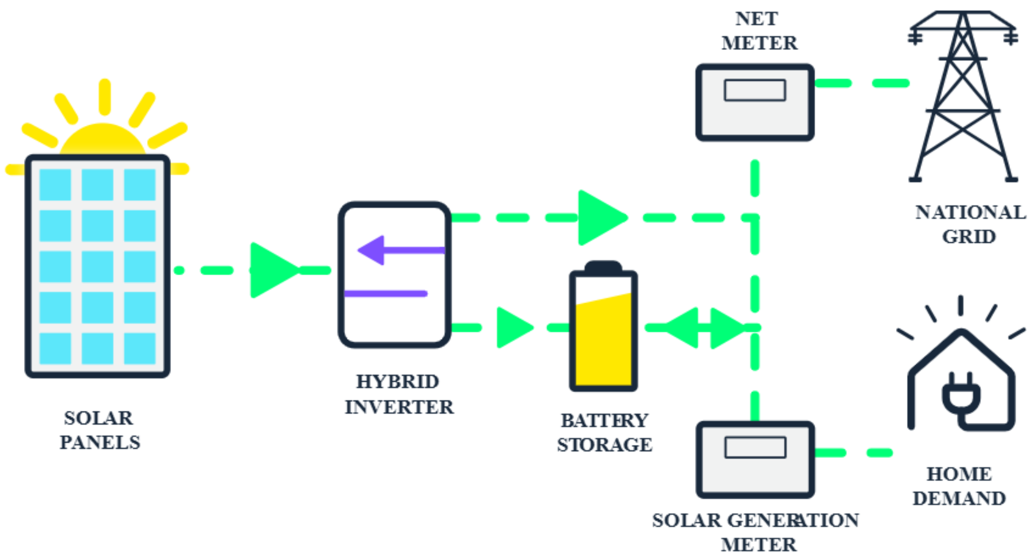

Figure 1.6: Hybrid Solar System

1.7.4. Grid-Connected PV Systems with Storage

- Similar to grid-tied systems but include battery storage.
- Provide backup power during grid outages and allow for energy management (e.g., time-of-use optimization).
- Sometimes referred to as "hybrid" or "backup power" systems.

1.8. PV generator

A PV (photovoltaic) generator is a key component in a solar power system, consisting of multiple photovoltaic modules connected together to convert solar energy into electrical energy. It is typically made up of groups of solar modules connected in series to form "strings," and these strings are then connected in parallel to form the entire generator. The total voltage of a string is the sum of the voltages of each module, while the total current of the generator is the sum of the currents from each string. This configuration allows the PV generator to produce a usable electrical output for various applications.

In summary, a PV generator is an assembly of solar modules configured to convert sunlight into electrical energy, forming the heart of any photovoltaic system and enabling the generation of clean, renewable electricity

1.9. Solar Panel String

The "solar panel string" is the most basic and important concept in solar panel wiring. This is simply several PV modules wired in series or parallel.

1.9.1. Series Connection

Solar panels feature positive and negative terminals. Wiring solar panels in series means wiring the positive terminal of a module to the negative of the following, and so on for the whole string. This wiring type increases the output voltage, which can be measured at the available terminals.

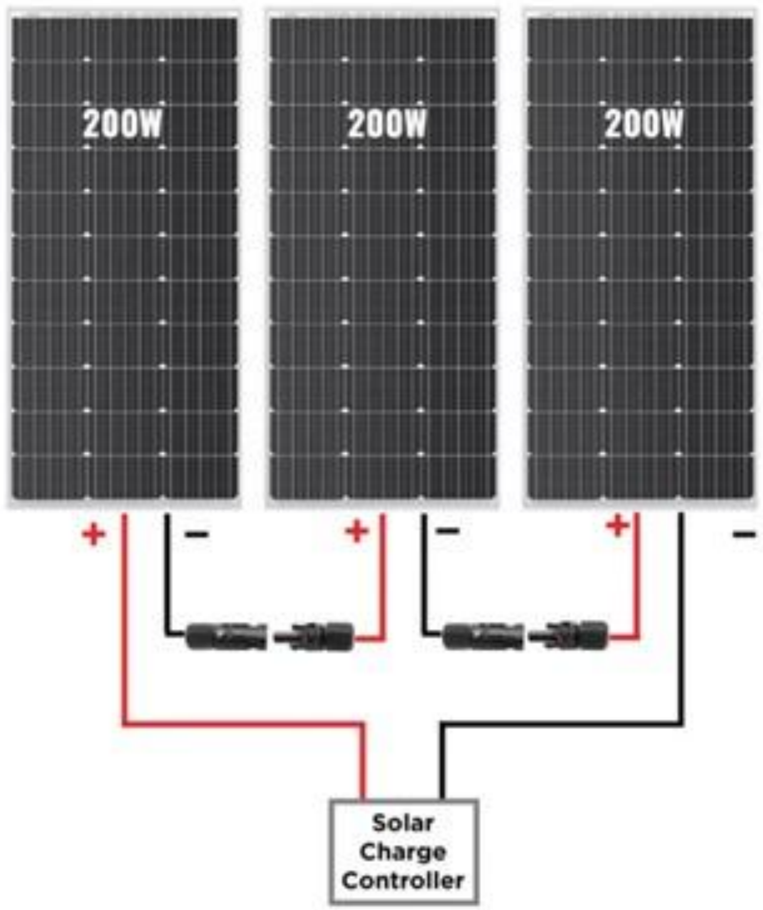

Figure 1.7: Solar panels in series.

1.9.2. Parallel Connection

Wiring solar panels in parallel increases the output current, while keeping the voltage constant. The output current is the sum of all currents generated by the modules in the string.

Solar panels wired in parallel also have to meet NEC regulations. This includes conductor size and overcurrent devices. This is calculated by oversizing the Short Circuit Current (Isc) by 125%, considering the number of modules in the system, as specified in the NEC Article 690.8. [12]

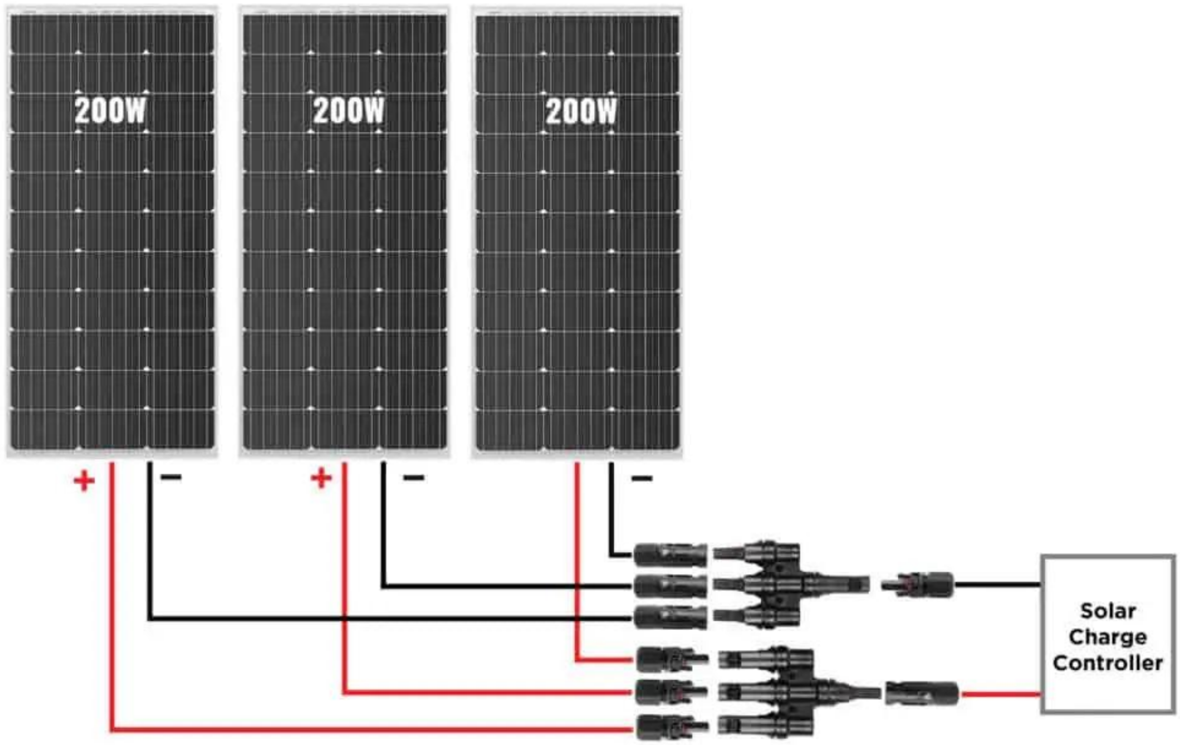

Figure 1.8: Solar panels in parallel.

1.9.3. Series-Parallel Connection

There is a solar panel wiring combining series and parallel connections, known as series-parallel. This connection wires solar panels in series by connecting positive to negative terminals to increase voltage and connects these strings in parallel. All solar panel strings connected in parallel have to feature the same voltage, and they also have to comply with the NEC 690.7, NEC 690.8(A)(1), and NEC 690.8(A)(2). Modules need to be the same model in all cases in order to provide optimum performance on the system.

1.10. Advantages and disadvantages of photovoltaic systems

1.10.1. Advantages

- Sustainable energy source: photovoltaic systems use the sun's energy, making them a sustainable energy source that is independent of fossil fuels.
- Cost-effectiveness: although the initial cost of a photovoltaic system can be high, it can be very cost-effective in the long run because energy production is free and operating costs are minimal.
- Low maintenance: photovoltaic systems require little maintenance and have a long-life span, making them a very reliable energy source.
- Flexibility: photovoltaic systems can be installed in many different places, such as on the roofs of buildings, on open spaces or on mobile platforms. This allows for a high degree of flexibility in placement and use.
- Independence from electricity suppliers: by installing a photovoltaic system, you become more independent of the electricity supply and can ensure your own energy supply.

1.10.2. Disadvantages

- Weather dependency: the power generated by a photovoltaic system is weather dependent and can be greatly reduced by bad weather, such as clouds. This can affect the efficiency of the system.
- Initial cost: the initial cost of a photovoltaic system can be high, although the cost has decreased in recent years.
- Space requirements: a photovoltaic system needs sufficient space to be used effectively, which is often a challenge in urban environments.
- Power storage: storing excess energy can be a challenge, as it often comes at an additional cost.
- Dependency on sunlight: Since power generation from a photovoltaic system depends on sunlight intensity, it is not always the best choice for locations with limited sunlight. [13]

1.11. Modeling of a PV Cell

A single solar cell can be represented as a component of an electrical circuit. It contains a p–n junction called as a diode, a photocurrent generator represented a generation of current from light and two resistors, one is arranged in series and another one is in parallel which described the Joule effect and recombination losses. Then this combination is called as a single diode solar cell model (KRS 18). The solar PV device can be represented as an ideal solar cell in Figure 1.3.

The current source I_{ph} represents the cell photocurrent. R_p and R_s are the intrinsic parallel and series resistances of the cell, respectively. Usually, the value of R_p is very large and that of R_s is very small, hence they may be neglected to simplify the analysis.

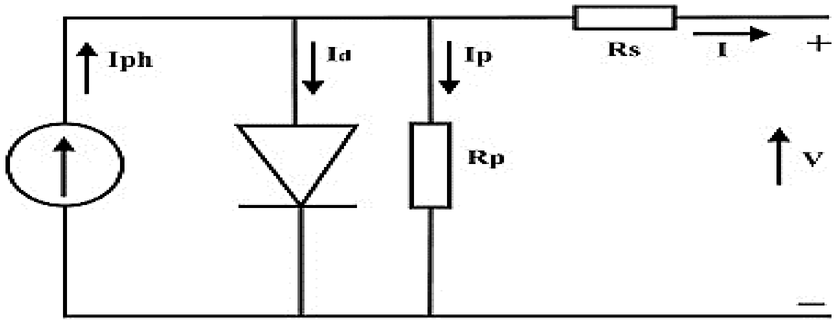

Figure 1.9: Model of a PV cell.

The PV panel can be modelled mathematically as given in equation (1)-(4).

Module photo-current:

$$I_{ph} = [I_{SCr} + K_i(T - 298)] * \lambda/1000 \tag{1}$$

The module reverse saturation current - I_{rs}:

$$I_{rs} = I_{SCr}/[\exp(qV_{OC}/N_S kAT) - 1] \tag{2}$$

The module saturation current I0 varies with the cell temperature, which is given by

$$I_O = I_{rs}[\frac{T}{T_r}]^3 \exp\left[\frac{q*E_{g0}}{Bk}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right] \tag{3}$$

The current output of PV module is:

$$I_{PV} = N_P * I_{ph} - N_P * I_0[\exp\left\{\frac{q*(V_{PV}+I_{PV}R_S)}{N_S AkT}\right\} - 1] \tag{4}$$

Where $V_{pv} = V_{oc}$, $N_p = 1$ and $N_s = 36$

1.12. Characterization of the PV module

In this study, we simulated the KC200GT photovoltaic module, which consists of 54 mono crystalline silicon solar cells measuring 125.125mm connected in series.

The module can produce a maximum power of 200 watts at 32 volts. This allowed us to determine the power as a function of voltage and the current as a function of the voltage of the module studied for an irradiance of 1000 W/m2.

The electrical characteristics of the KC200GT Photovoltaic module under standard test conditions are shown in Table 1.1:

Table 1.1: Electrical characteristics of the PV module KC200GT under standard test conditions.

Total number of cells in series (N_s)	54
Rated power (W)	200.143 W
Short-circuit current (I_{sc})	8.21 A
Open circuit voltage (V_{oc})	32.9 V
Current at Maximum power (I_{mp})	7.61 A
Voltage at Maximum power (V_{mp})	26.3 V

1.13. Simulation of the PV array

Based on the mathematical model of the solar cell developed in the MATLAB / SimPower System tool, the SIMULINK schematic block is shown in Figure 1.5.

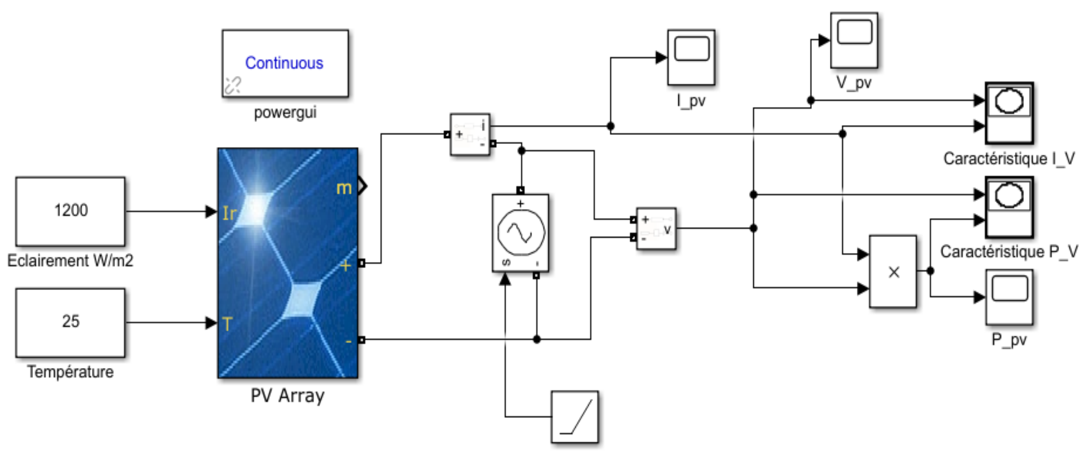

Figure 1.10: Block diagram of the solar module in SIMULINK « KC200GT ».

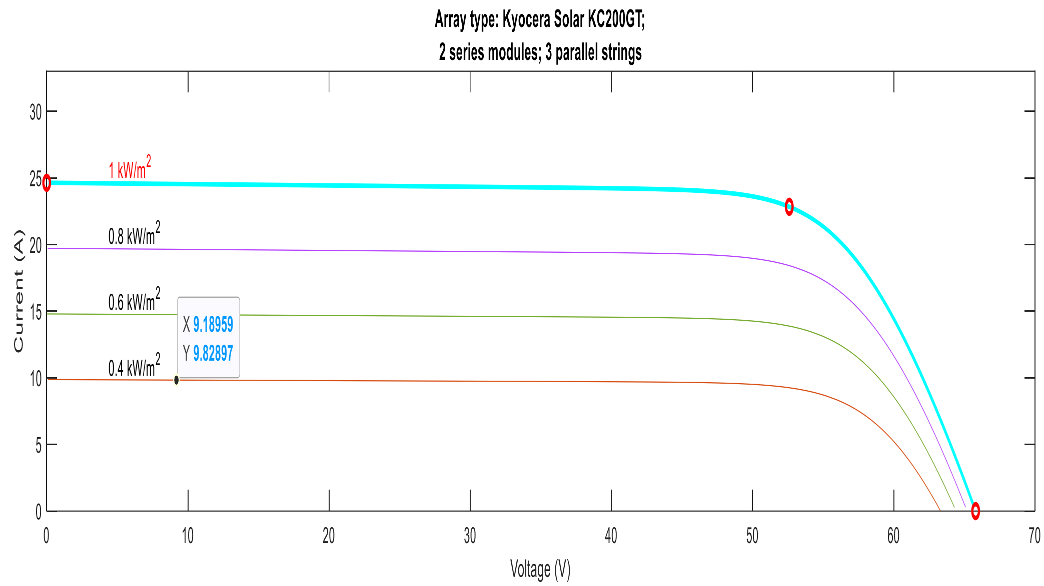

Figure 1.11: Effect of Irradiance on the Current-Voltage Characteristic.

The diagram shows the voltage-current (I-V) curves of a solar panel under different irradiance levels, where the current increases with higher solar irradiance. The voltage remains relatively stable, while the maximum power point shifts with changing irradiance.

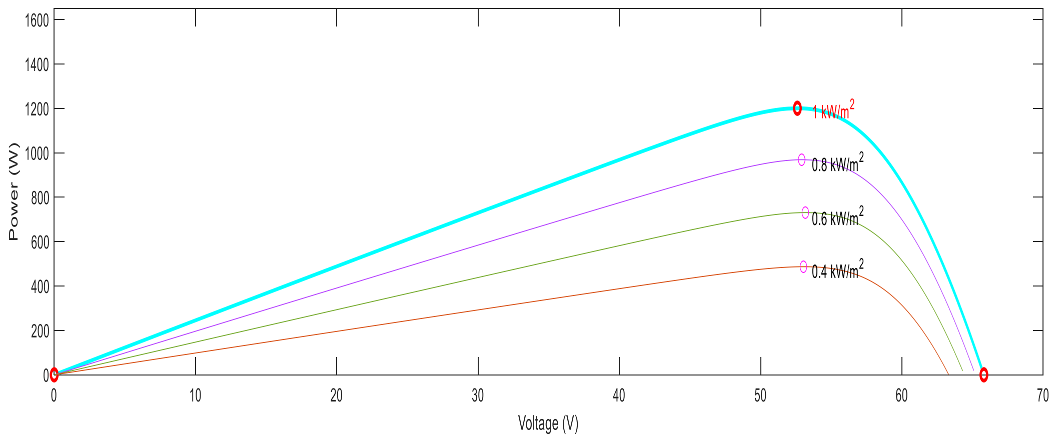

Figure 1.12: Effect of Irradiance on the Power-Voltage Characteristic.

The diagram shows the power-voltage (P-V) curves of a solar panel under different irradiance levels, where the output power increases with higher irradiance and reaches a maximum at the Maximum Power Point (MPP), which shifts depending on the irradiance level

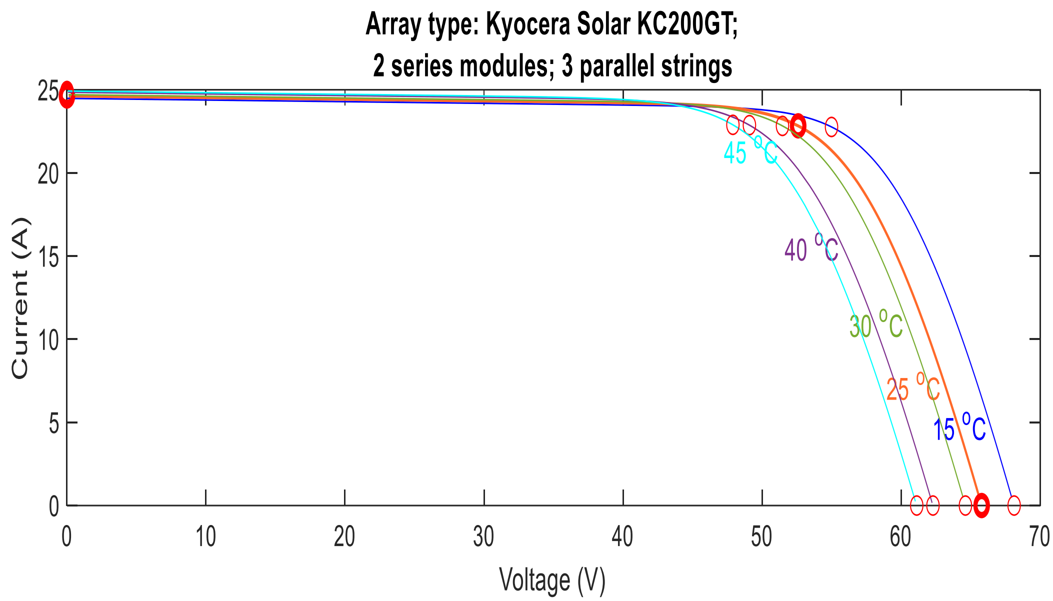

Figure 1.13: Effect of Temperature on the Current-Voltage Characteristic.

The diagram shows the current-voltage (I-V) characteristics of a solar panel at different temperatures (from 15°C to 45°C). The current remains nearly constant, while the voltage decreases significantly with increasing temperature, leading to a reduction in overall power output.

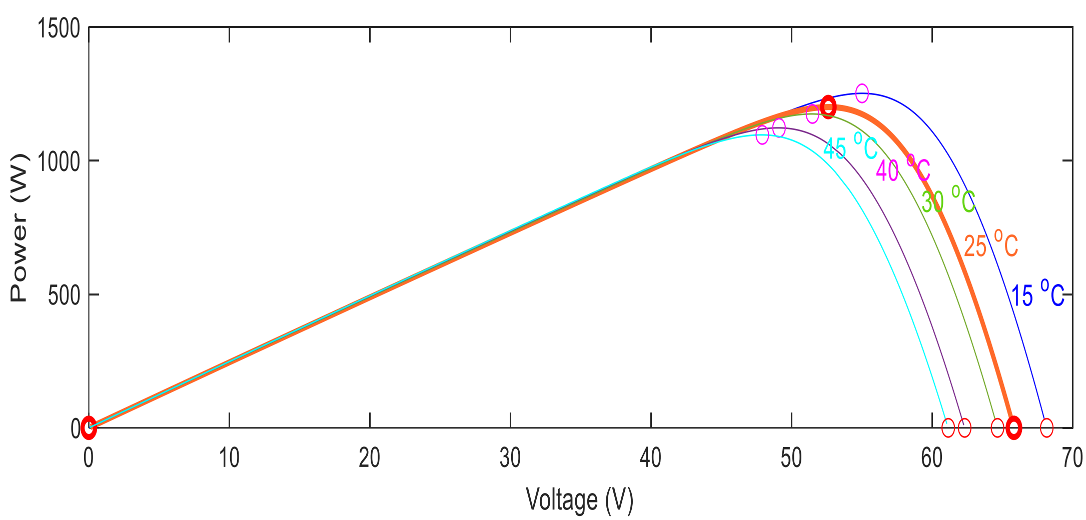

Figure 1.14: Effect of Temperature on the Power-Voltage Characteristic.

The diagram shows the power-voltage (P-V) characteristics of a solar panel at different temperatures (from 15°C to 45°C). The output power decreases with increasing temperature due to the reduction in voltage at the Maximum Power Point (MPP), indicating better performance at lower temperatures.

1.14. Conclusion

In this first chapter we presented generalities on the production systems of electrical energy which are based on the photovoltaic effect, in this context, statistics on world production were presented and the application of the PV system, then the principle of conversion, cell types and its modeling as well as the different types of converters and their modeling and topology, we have dedicated our studies to this kind of PV cells KC200GT, as a result, the most widely used to raise the output voltage of PV Systems is Boost converters and the development is still being carried out by adding more complex approaches to achieve higher performance levels. In the next chapter, we will present the MPPT techniques.

CHAPTER 2: Techniques of Maximum Power Point Tracking (MPPT)

2.1. Introduction

A photovoltaic generator operates over a broad operating envelope defined by its current-voltage (I-V) characteristics. However, it delivers maximum output power only at a unique operating point known as MPP, which corresponds to specific values of voltage and current. This point is not fixed; it dynamically shifts in response to variations in solar irradiance and cell temperature, due to the nonlinear and environment-dependent nature of the PV module’s electrical behavior.

To maintain operation at the MPP under changing environmental conditions, power conditioning units (typically DC-DC converters) are deployed between the PV array and the electrical load. These converters implement MPPT algorithms, which continuously perturb and observe the system’s operating point to converge on and track the instantaneous MPP in real time. By dynamically adjusting the input impedance seen by the PV array, MPPT controllers maximize the power extracted from the generator, ensuring optimal energy transfer efficiency regardless of irradiance or thermal fluctuations.

2.2. DC-DC converter

DC-DC converters constitute a fundamental category of power electronic circuits designed to regulate and convert direct current (DC) voltages from one level to another. These systems accept a DC input voltage and provide a controlled DC output voltage that may be either stepped up (boosted) or stepped down (buck) relative to the input level. Their operation is limited to DC power sources, as they are not intended for use with alternating current (AC) inputs. DC-DC converters are critical in applications requiring efficient voltage adaptation, such as in renewable energy systems, electric vehicles, and portable electronic.[14]

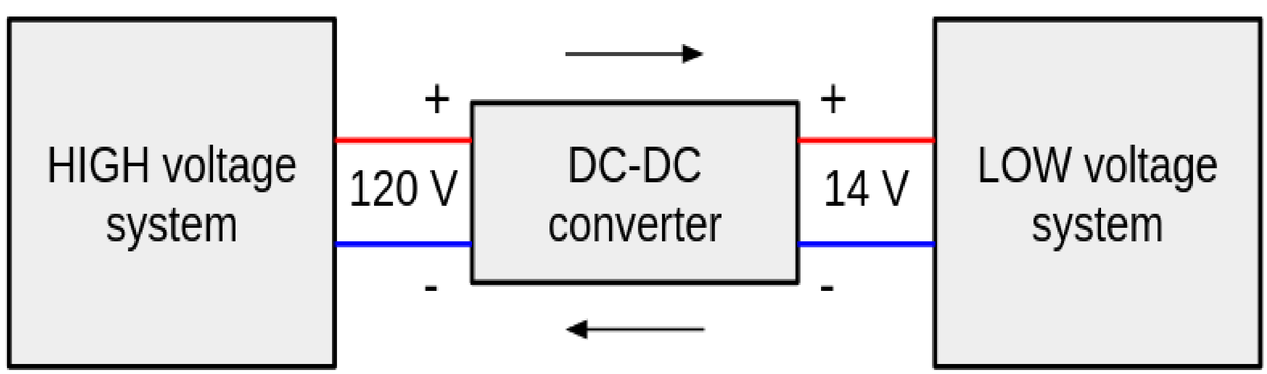

Figure 2.1: Principle of operation of a DC-DC convert.

If we have two electrical systems, operating at different voltage levels, one high level (140 V) and another one low level (14 V), a DC-DC converter can convert the voltage between them, from high to low or from low to high. The conversion from one voltage level to another voltage lever is done with some power losses. Depending on the operating point of the DC-DC converter (voltage and current) and the type of converter, the efficiency can be between 75 % to 95 % or more. [14]

2.2.1. Efficiency of DC-DC converters

The electric power P [W] is the product between voltage U [V] and electrical current I [A].

$$P = U \times I \tag{5}$$

If, for example, the input voltage U_{in} = 120 V and the maximum current I_{in} = 5 A, this will give an input power of:

$P_{in} = 120.5 = 600\ w$

Since the electrical power is conserved ($P_{out} = P_{in}$) and we assume that the DC-DC converter has no losses (100 % efficiency), for an output voltage U_{out} = 14 V, we can calculate the output current as:

$I_{out} = \frac{P_{out}}{U_{out}} = \frac{600}{14} = 42.86\ A$

In reality there will be some losses associated with the conversion and the maximum output current will be less than the one calculated for 100 % efficiency.

The efficiency of the DC-DC converter is calculated as:

$$\eta\ \% = (\frac{P_{out}}{P_{in}}) \times 100 \tag{6}$$

There are several types of DC-DC converters. The most common classification is from the ratio between the input and output voltage point of view:

- **Boost DC-DC Converters**
- **Buck DC-DC Converters**

In a boost DC-DC converter, the output voltage is higher than the input voltage. Due to power conservation (if we ignore the losses), the output current will be lower than the input current.

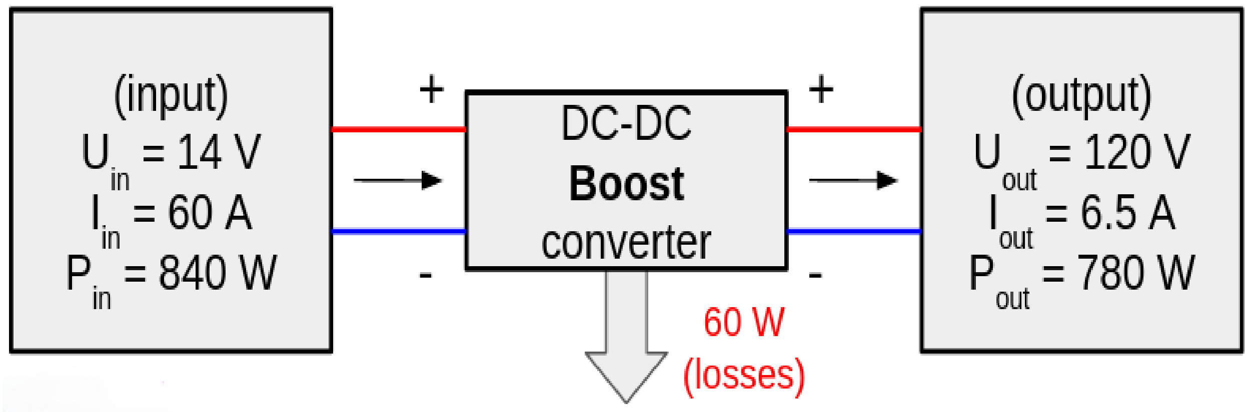

Figure 2.2: Principle of operation of a DC-DC boost converter.

For this example, the efficiency of the boost DC-DC converter is:

$$\eta = \left(\frac{780}{840}\right) \times 100 = 92.86\ \%$$

In a buck DC-DC converter, the output voltage is lower than the input voltage. Due to power conservation (if we ignore the losses), the output current will be higher than the input current.

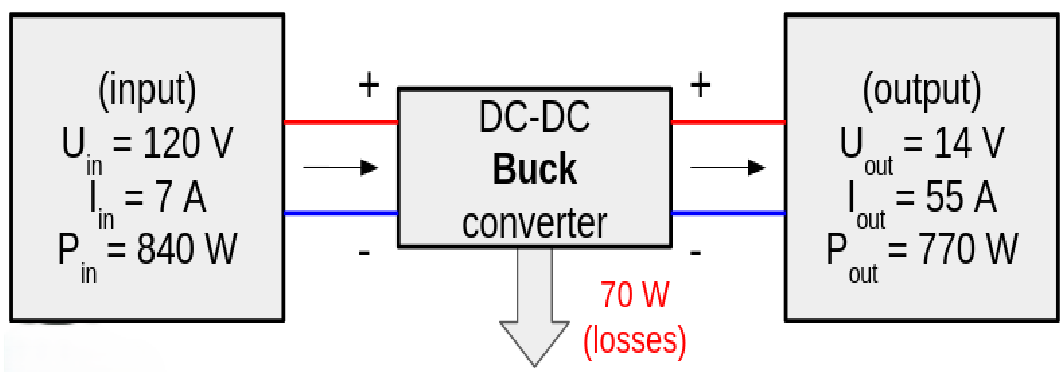

Figure 2.3: Principle of operation of a DC-DC buck converter.

or this example, the efficiency of the buck DC-DC converter is:

$$\eta = \left(\frac{770}{840}\right) \times 100 = 91.67\ \%$$

2.2.2. Classification of DC-DC converters

There are multiple types of DC-DC converters. The simplest form of DC-DC converter is the linear converter, also called linear voltage regulator.

A linear voltage regulator can only work as a buck DC-DC converter, which means that will only lower a higher voltage level. Being a regulator, it also ensures that the output voltage is maintained at a specific value, even if the output load is variable.

A more efficient type of DC-DC converters is the switching DC-DC converter. There are several topologies of switching DC-DC converters, the most common being presented in the image below.

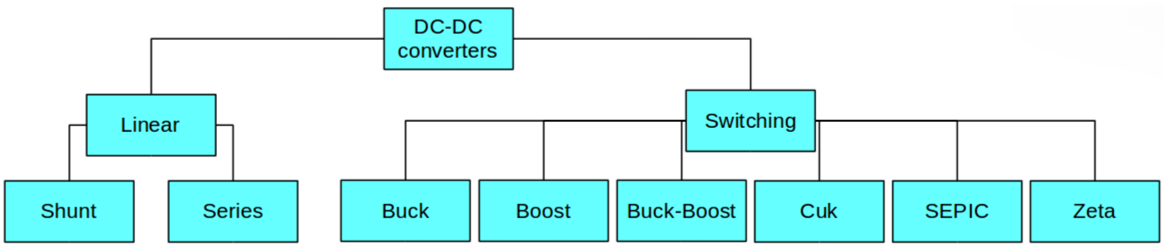

Figure 2.4: Classification of DC-DC converters.

2.3. Maximum Power Point Tracking

MPPT is a control technique designed to continuously operate a nonlinear electrical generator (such as a PV or wind generator) at its maximum power point. It is typically integrated with an intermediate adaptation stage that adjusts the duty cycle of a DC-DC converter to ensure maximum power delivery. In PV systems, the MPPT controller monitors environmental conditions such as temperature and solar irradiance and dynamically adjusts the operating point of the system to maintain optimal performance at all times. By controlling the static converter that connects the load to the PV module, the MPPT ensures the load consistently receives the maximum available power. The system under study includes a photovoltaic generator (GPV), a DC-DC converter, and a motor-pump unit at the output. The converter is driven by a pulse-width modulation (PWM) signal based on the MPPT strategy to extract maximum energy under varying environmental conditions.[15]

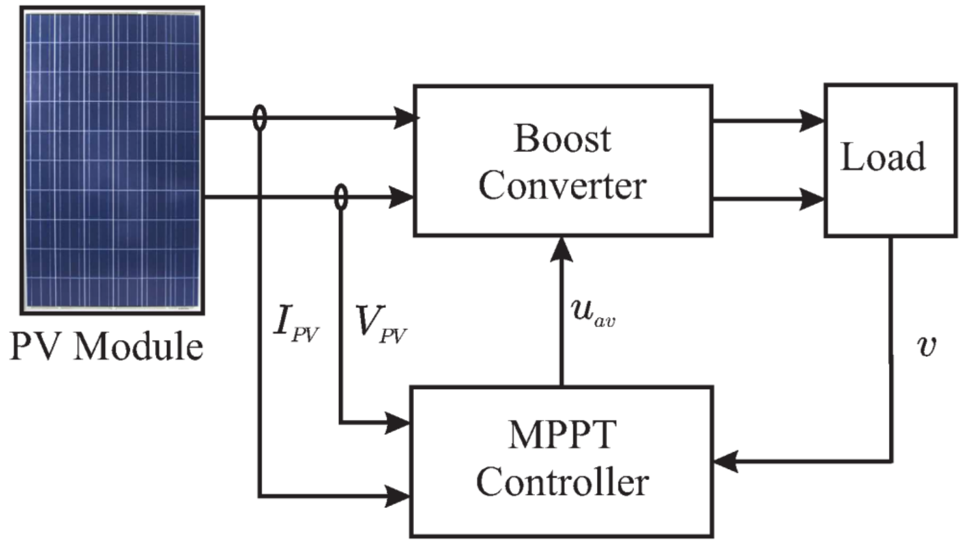

Figure 2.5: Basic MPPT of Photovoltaic Energy Conversion Chain.

The MPPT controller modulates the duty cycle of the power converter using a suitable control signal to ensure that the photovoltaic generator (PVG) delivers its maximum available power. Depending on the tracking method used, the MPPT algorithm can range from lower to upper voltage value until reach to MPP. Typically, it monitors variations in input voltage and current (which affect the PVG's power output) and adjusts the duty cycle accordingly until reach to MPP, as shown in Figure 2.6.

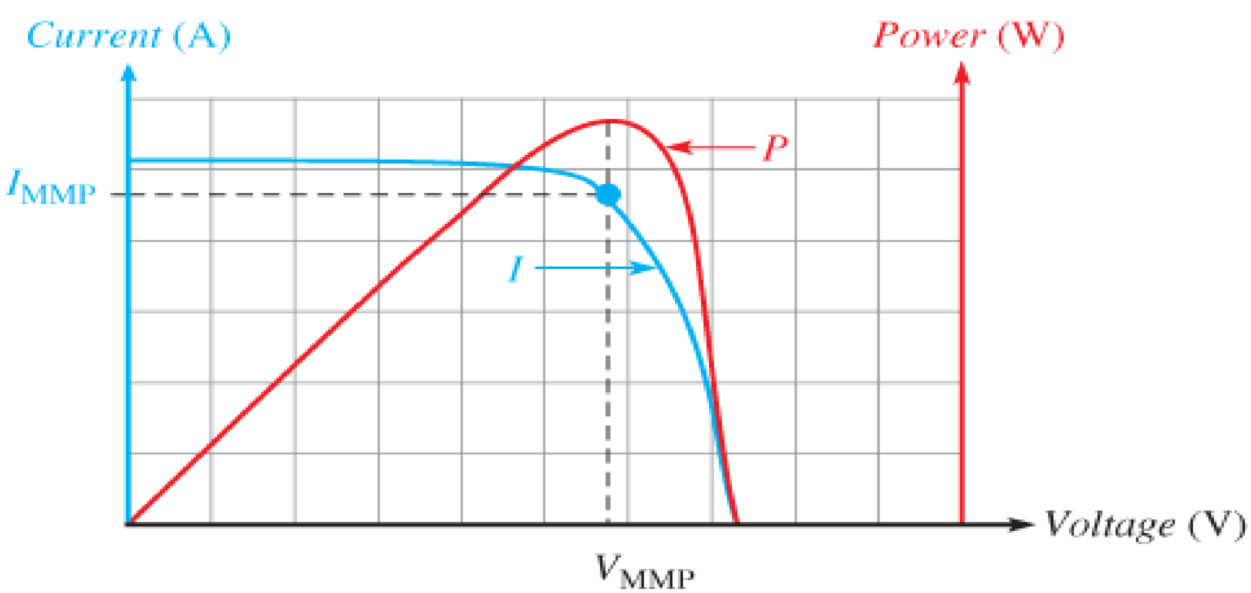

Figure 2.6: Principle of MPPT algorithm.

The tracking algorithm works based on the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point as shown in Figure 2.6.

$$\frac{\partial P}{\partial V} = 0 \quad for \quad V = V_{mp} \tag{7}$$

$$\frac{\partial P}{\partial V} > 0 \quad for \quad V < V_{mp} \tag{8}$$

$$\frac{\partial P}{\partial V} < 0 \quad for \quad V > V_{mp} \tag{9}$$

The module *P*-*V* characteristics are shown on figure 2.6 that shows the derivative greater than zero to the left of the peak point and is less than zero to the right. The peak power is reached with the help of a DC-DC converter by adjusting its duty cycle. An automatic tracking can be performed by utilizing various algorithms such as P&O, Incremental Conductance, Open Circuit Voltage, Short Circuit Current. We mainly concentrate on the P&O algorithm.

2.4. Categorization of MPPT Techniques

MPPT techniques can be categorized based on several criteria, one common approach classifies them according to their hardware implementation: Classique, soft meta heuristique and hybrid. However, a more insightful classification considers the nature of the tracking strategy (whether it is direct or indirect) and the type of input parameters used by the control algorithm, such as voltage, current or poth of them [16].

2.4.1. MPPT Based on PV system

MPPT algorithms rely on PV system parameters primarily voltage, current, irradiance, and temperature to track and maintain operation at the MPP. These parameters influence the PV module's voltage and current characteristics, which in turn determine the power output.

Voltage and Current Measurement: Accurate measurement of PV voltage and current is crucial for effective MPPT. Algorithms adjust the operating voltage to maximize power output by interpreting these measurements.

Environmental Parameters: Solar irradiance and cell temperature significantly affect the MPP. For example, the maximum power voltage can vary from about 15 V on hot days to 18 V on cold days for typical modules. MPPT algorithms incorporate these parameters to adaptively track the MPP under changing conditions

2.4.2. MPPT Search Type

2.4.2.1. Indirect Methods

In indirect methods, databases containing the physical values of the PV panel are typically used to generate control signals under various climatic conditions (temperature, sunlight). These methods which are specifically designed for PV systems, include the open-circuit voltage (Voc) method, the short-circuit current (Icc) method, and the MPPT method based on artificial intelligence (AI).

These controllers are advantageous due to their simplicity in implementation. They are primarily intended for low-cost and less accurate systems, which are expected to operate in geographical areas with minimal climatic variations [17].

2.4.2.2. Direct Methods

The direct method uses instantaneous values of output voltage or current to generate control signals, with the algorithm based on variations in these measurements. The advantage of these algorithms is that they do not require prior knowledge of the characteristics of the PV panels. As a result, they can respond to unpredictable changes in the PV system's operation. In this method, the operating point voltage is incremented at regular intervals. If the output power increases, the search direction is maintained for the next step; otherwise, it is reversed [17].

2.5. Common MPPT Algorithms

Since the publication of the first MPPT control law in 1968 (specifically designed for renewable energy sources like photovoltaic systems) numerous studies and control strategies have emerged in the literature. Due to the vast number of contributions in this area, we have categorized the various MPPT algorithms based on their underlying principles. In addition to the core concept, this classification also considers criteria such as tracking accuracy and response speed, allowing for a comparative evaluation of different approaches. This manuscript focuses only on algorithms that present a clearly defined search methodology, which are briefly analyzed in the following sections [17].

2.5.1. Hill Climbing Method

The Hill Climbing control technique involves perturbing the duty cycle while simultaneously altering the voltage. This results in a shift of the operating point along the power–duty cycle curve of the photovoltaic generator, as illustrated conceptually in Figure 2.7, which shows the relationship between output power and duty cycle [15].

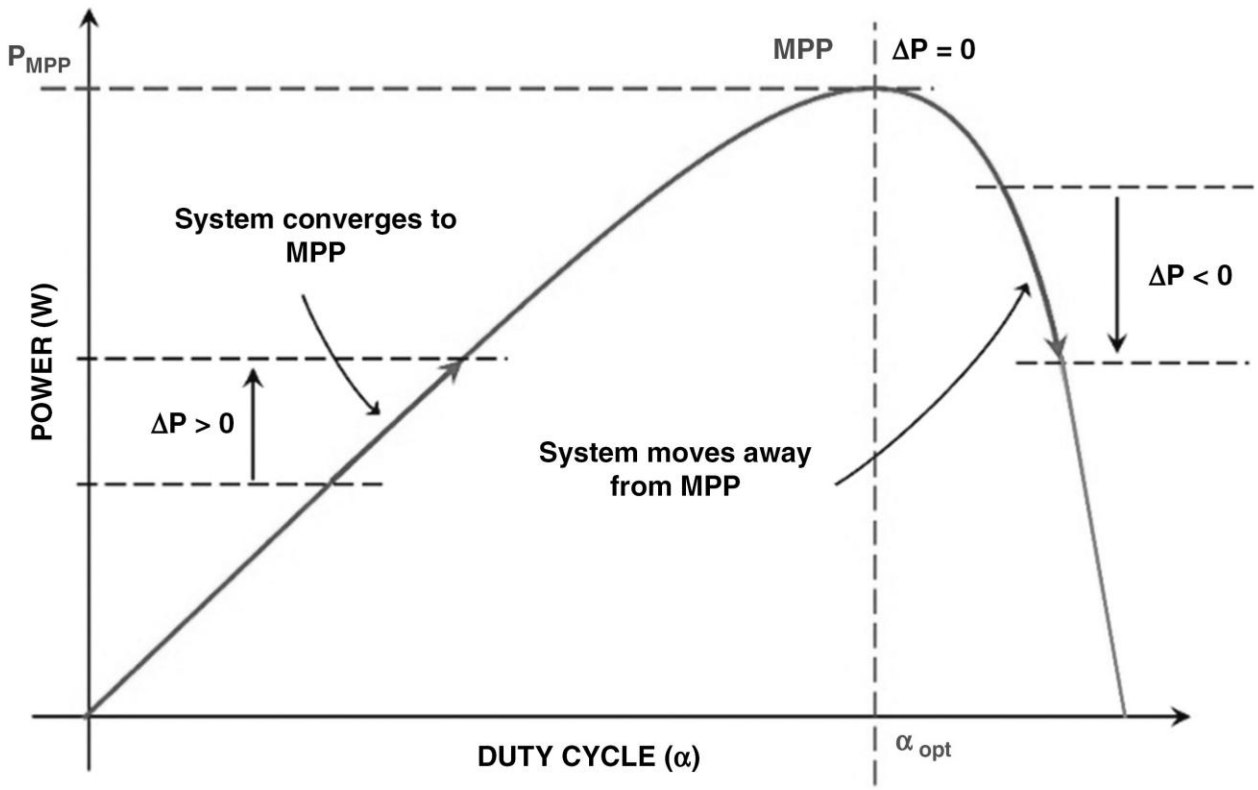

Figure 2.7: Research method of HC to reach MPP [15].

If a positive increment in the duty cycle leads to an increase in output power, it indicates that the operating point is located to the left of the MPP, and the direction of the perturbation should be maintained.

Conversely, if the power decreases following a positive increment, the operating point lies to the right of the MPP**,** and the direction of perturbation must be reversed [15].

The variable slope takes the value of either 1 or -1 depending on the direction of the search required to increase power output. The parameter a represents the step size used to increment the duty cycle [15].

One of the main advantages of this method is that it does not require prior knowledge of the actual current–voltage characteristics of the photovoltaic generator.

2.5.2. Perturb and Observe Method

The P&O, as the name itself states that the algorithm is based on the observation of the array output power and on the perturbation (increment or decrement) of the power based on increments of the array voltage or current. The algorithm continuously increments or decrements the reference current or voltage based on the value of the previous power sample. The P&O is the simplest method which senses the PV array voltage and the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't step at the MPP and keeps on perturbing in both the directions.

The P&O algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resulting changes in power ΔP is positive, then we are going in the direction of MPP and we keep on perturbing in the same direction. If ΔP is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed.

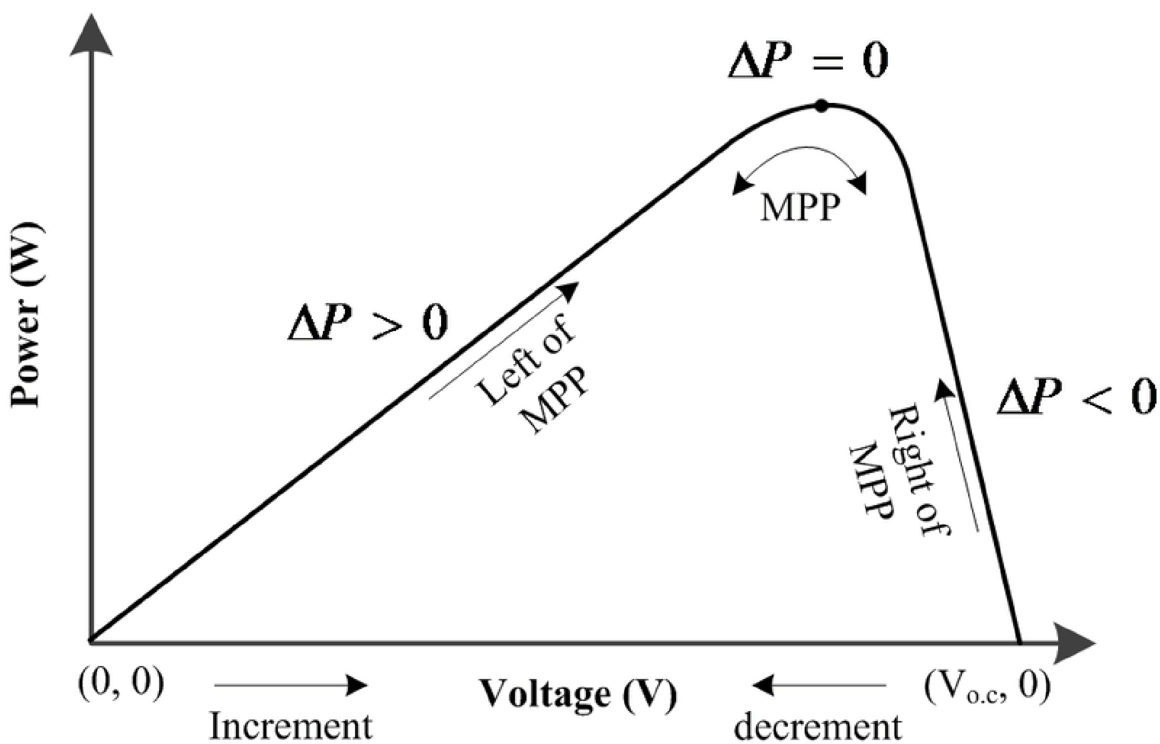

Figure 2.8: Research method of P&O to reach MPP.

The operation of the P&O technique is shown in Figure 2.8 analyses the plot of module output power versus voltage for a solar panel. The P&O algorithm operates by periodically perturbing the array terminal voltage or current and comparing the PV output power with that of the previous perturbation cycle. First a slight perturbation is introduced in the system, due to which the power of the module changes. If the power increases due to perturbation, then the perturbation is continued in that direction. After the peak power is reached, the power at the next instant decreases and hence after that the perturbation is reversed.

The P&O method has slow dynamic response, when there is a small increment in the value and low sampling rate is employed. Low increments are necessary to decrease the steady state error because the P&O always makes the operating point oscillate near the MPP. The lower the increment, the closer the system will be to the array MPP. The greater the increment, the faster the algorithm will work, but the steady state error will be increased. Considering that a low increment is necessary to achieve a satisfactory steady state error, the algorithm speed may be increased with a higher sampling rate. So, there is always a compromise between the increment and the sampling rate in the P&O method.

The common problem in P&O algorithms id the array terminal voltage is perturbed every MPPT cycle: therefore, when the MPP is reached, the output power oscillates around the maximum, resulting in power loss in the PV system. This is especially true in constant or slow-varying atmospheric conditions.

As shown in Figure 2.9 the P&O algorithm operates by periodically perturbing the operating voltage and comparing it with the previous instant. If the power difference ΔP and the voltage difference ΔV, both in the positive direction then there is an increase in the array voltage. If either the voltage difference or the power difference is in the negative direction then there is a decrease in the array voltage. If both the voltage and power difference are in the negative direction then there is an increase in the array voltage. Similarly, the next cycle is repeated until the Maximum Power Point is tracked

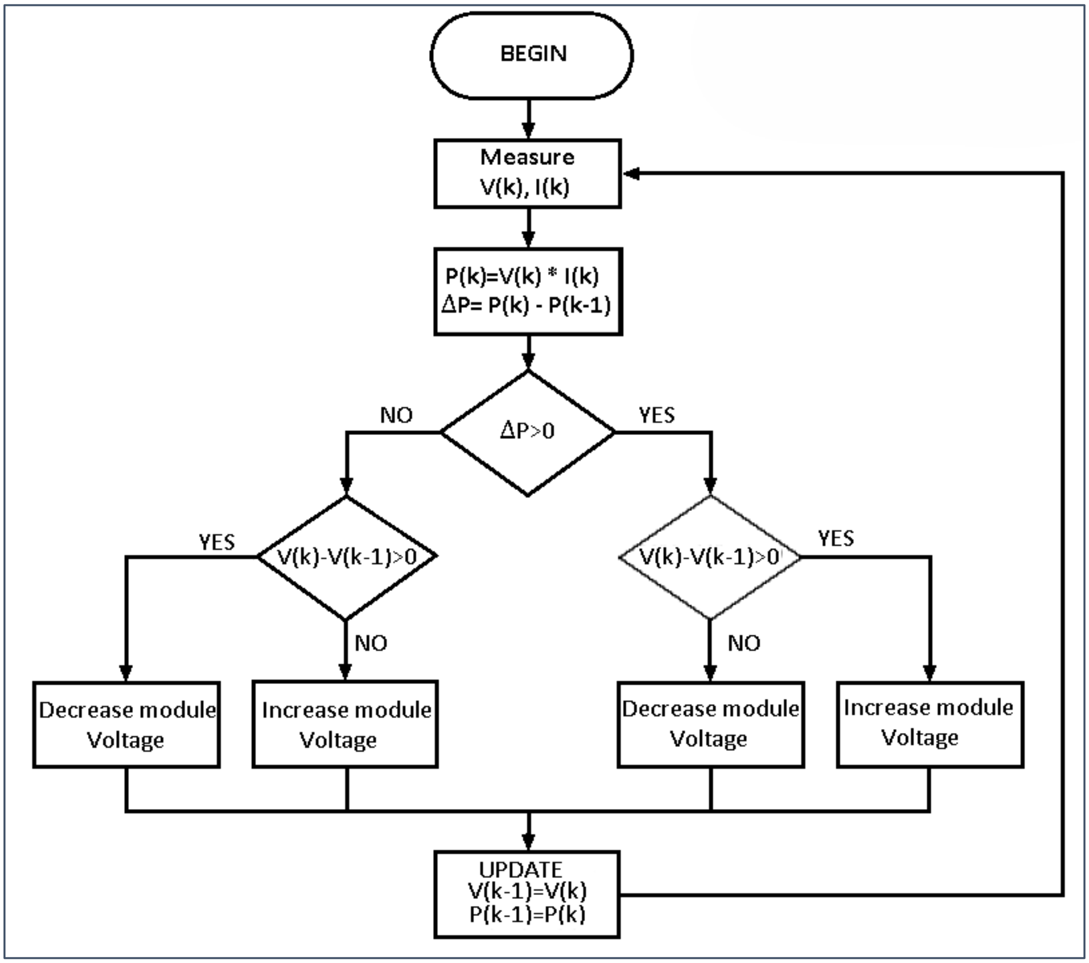

Figure 2.9: flowchart of P&O MPPT technique [18].

The Figure 2.5 shows that the PV array has been interfaced with the boost converter using a controlled voltage source. The inductor current which is same as the load current of the PV system is used as feedback for designing the PV array. The output of the filter which is the control signal is compared with the saw-tooth waveform to generate the PWM signal which is fed as gate signal to the switch S.

The output current of the PV array and the converter inductor current are same, so the MPPT algorithm can observe the array output power and optionally use the converter inductor current as the control variable. A comparison between actual and reference values for PV terminal voltage and maximum power available from PV array will control the duty ratio of boost converter.

The MPPT of photovoltaic power generation systems change with changing atmospheric conditions, an important consideration in the design of efficient PV systems is to track the MPP correctly. The dependence of power generated by a PV array and its MPPT on atmospheric conditions can readily be seen in the current-voltage and the power-voltage characteristics of PV arrays. Moreover, the MPPT changes with changing radiation and temperature, implying continuous adjustment of the array terminal voltage if maximum power is to be transferred.

2.5.3. Incremental Conductance

The working process of the INC algorithm is guided by the incremental conduction (ΔI/ΔV) of the characteristics of PV, which serve to detect the slope of the P-V characteristic curve (ΔP/ΔV) [19]. At the MPP point, this slope value will be zero, large from zero if on the left side of the MPP, and small from zero if on the right side. If the slope encountered is negative, then the operating point is shifted to the left by the controller by reducing the PV array voltage value, and vice versa. This happens until the slope becomes zero, and the adjustment of the voltage value will stop, indicating that the MPP has been reached [20]. Mathematically, it can be seen in equations (10) to equations (12) [20], [21].

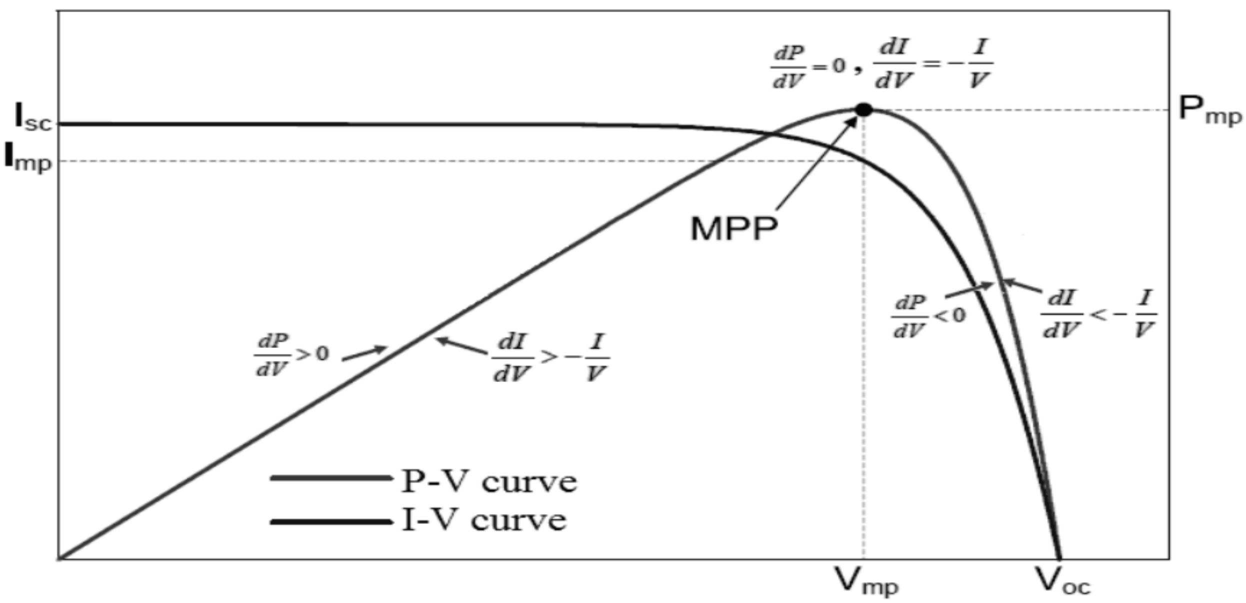

Figure 2.10: Research method of INC to reach MPP.

$$\frac{\Delta P}{\Delta V} = 0 \quad at\ the\ MPP \tag{10}$$

$$\frac{\Delta P}{\Delta V} > 0 \quad at\ the\ left\ position\ of\ the\ MPP \tag{11}$$

$$\frac{\Delta P}{\Delta V} < 0 \quad at\ the\ right\ position\ of\ the\ MPP \tag{12}$$

From equation (10) it can be redeveloped into equation (13) to (16)

$$\frac{\Delta P}{\Delta V} = \Delta(V \times I)/\Delta V = I + V\left(\frac{\Delta I}{\Delta V}\right) = 0 \tag{13}$$

Then:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad at\ the\ MPP \tag{14}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad at\ the\ left\ position\ of\ the\ MPP \tag{15}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad at\ the\ right\ of\ the\ MPP \tag{16}$$

The INC algorithm, as shown in Figure 2.11, is a conventional algorithm widely used nowadays because of its simple characteristics and cheaper financing and application [22], [23]

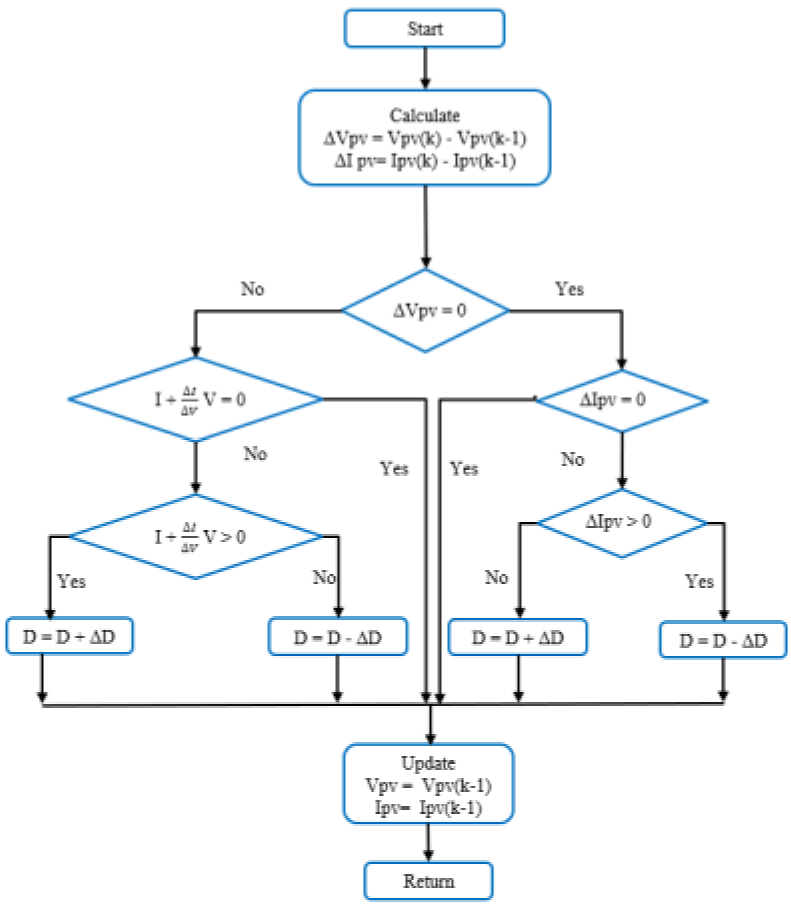

Figure 2.11: flowchart of INC MPPT technique.

2.6. Simulation and Result

Figure 2.12 shows a grid connected solar PV system. The boost MPPT converter supplies an inverter for 3 phase grid connections. The Simulink model of PV array with DC-DC boost converter using P&O. MPPT method is shown in figure 2.12 and its corresponding result is shown in figures 2. 13_17.

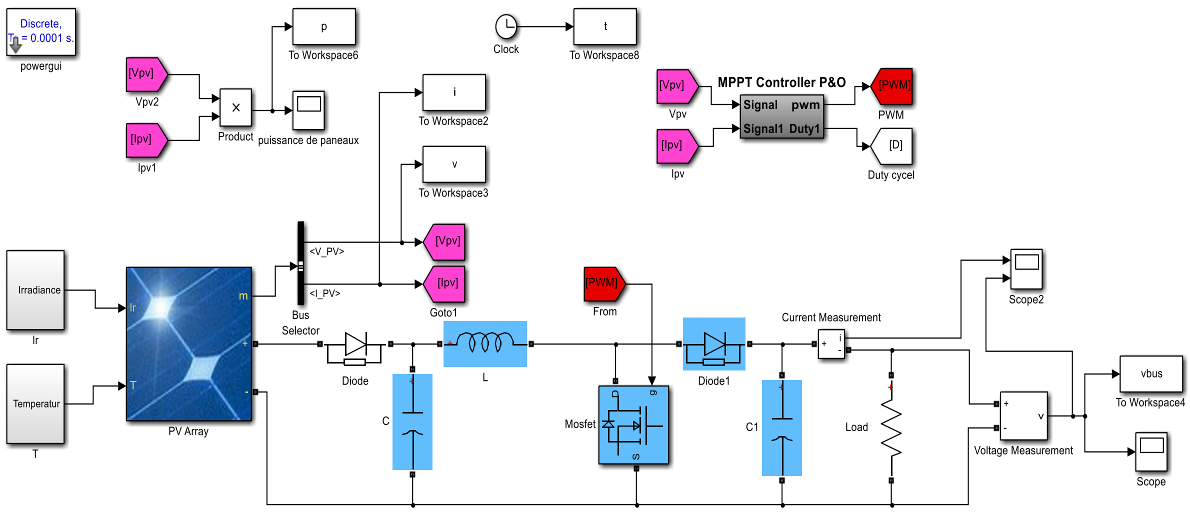

Figure 2.12: Simulink Model of P&O MPPT with DC-DC converter.

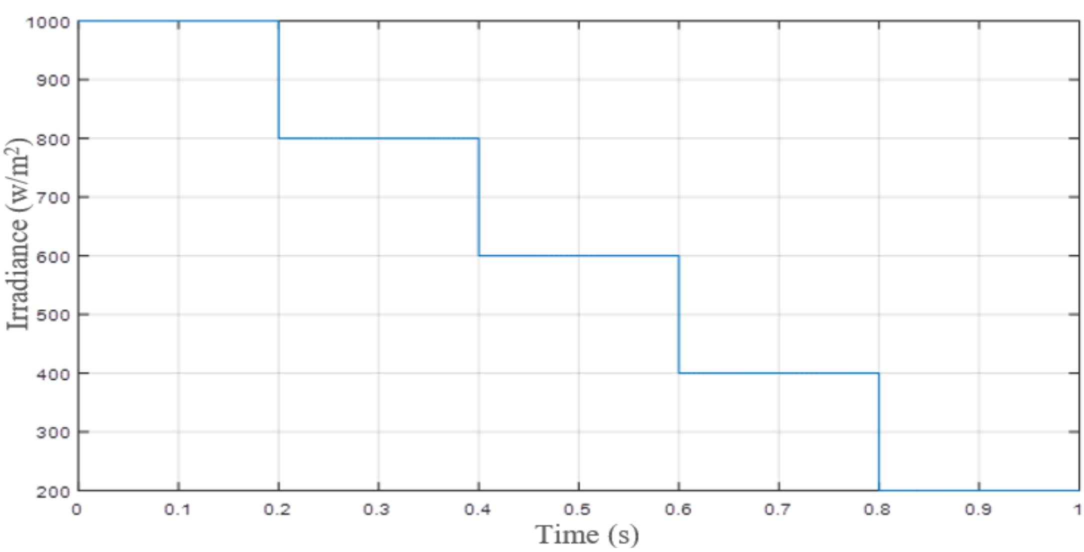

Figure 2.13: Irradiance Variation.

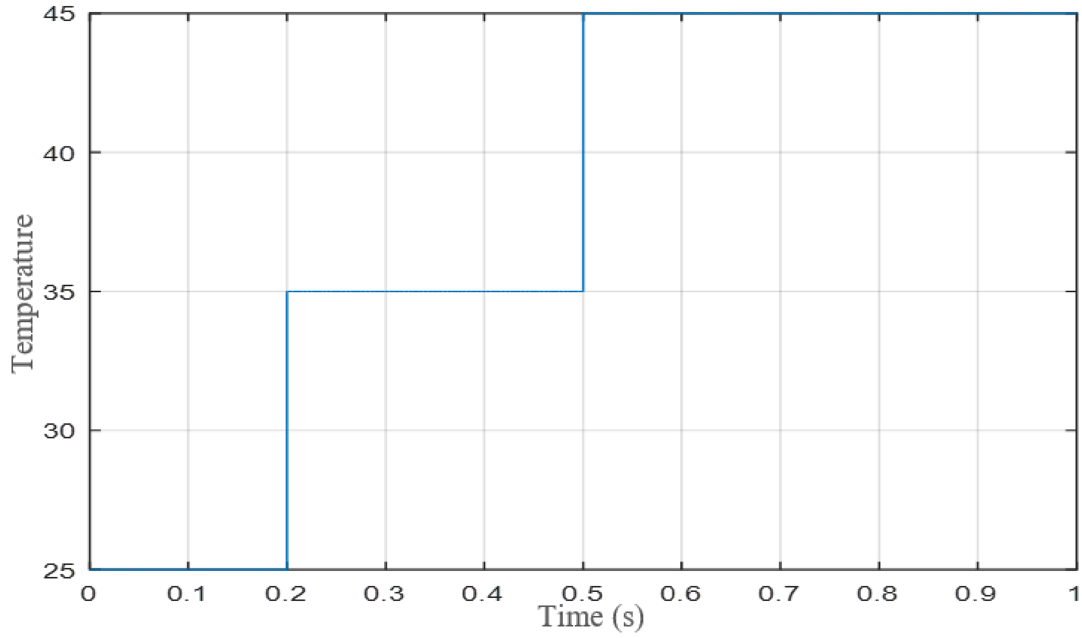

Figure 2.14: Temperature Variation.

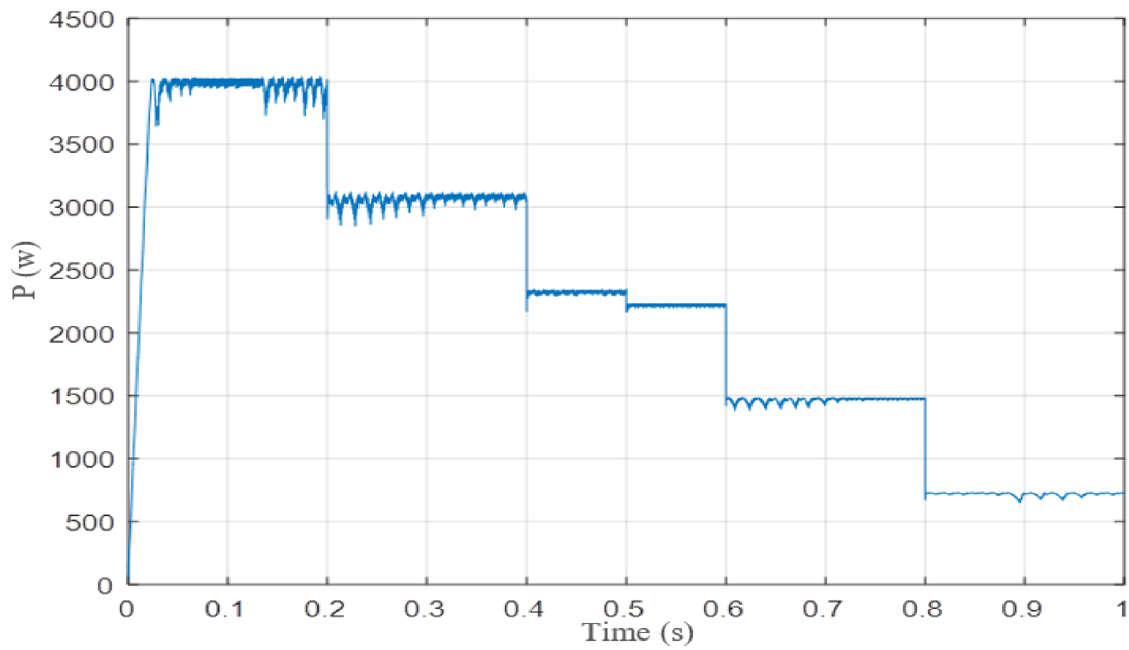

Figure 2.15: Simulation Results of Power Curves.

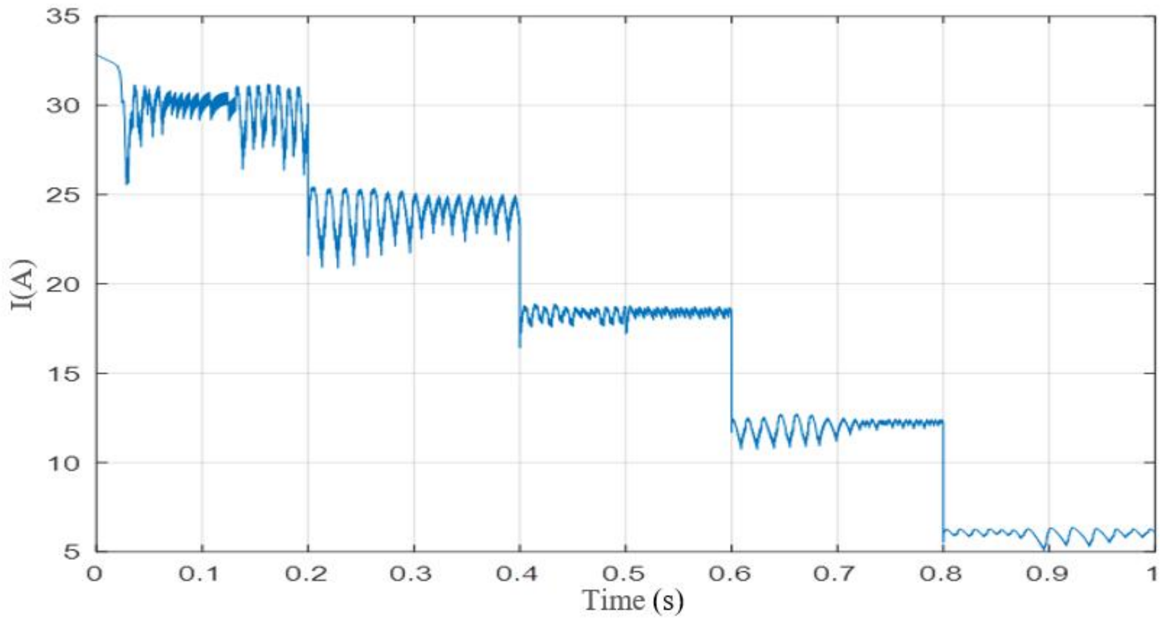

Figure 2.16: Simulation Results of the Current.

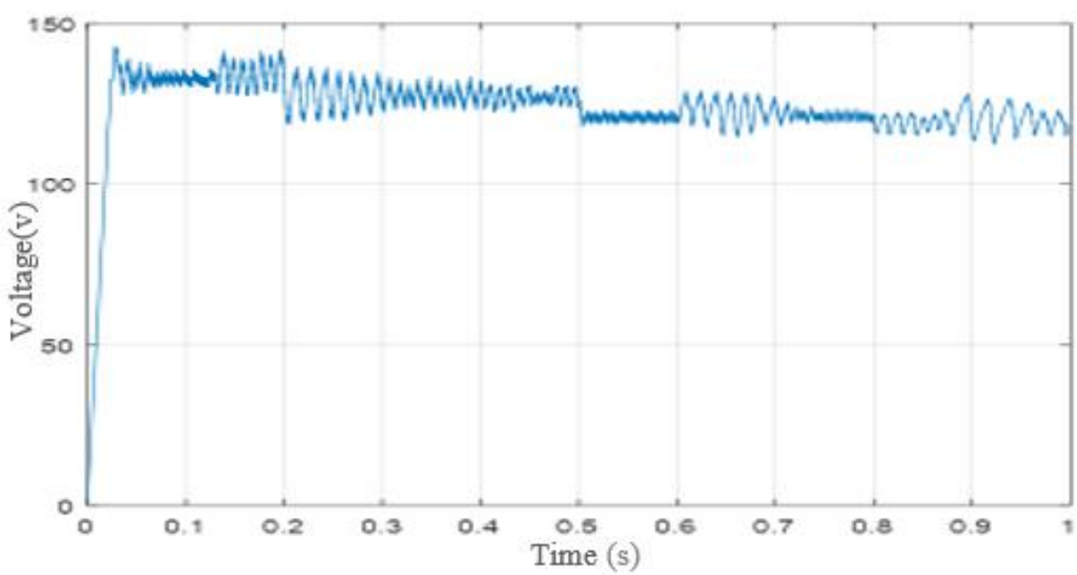

Figure 2.17: Simulation Results of PV Voltage Curves.

The Simulink model of PV array with DC-DC boost converter using INC MPPT method is shown in figure 2.18 and the simulation results of INC MPPT algorithm are illustrated in figures 2.19_23. The results show that the output current varies from 0.35A to 0.53A and the output voltage varies from 81.10V to 90.42V and an output power varies from 29.03W to 47.39W for a time period of 10 seconds.

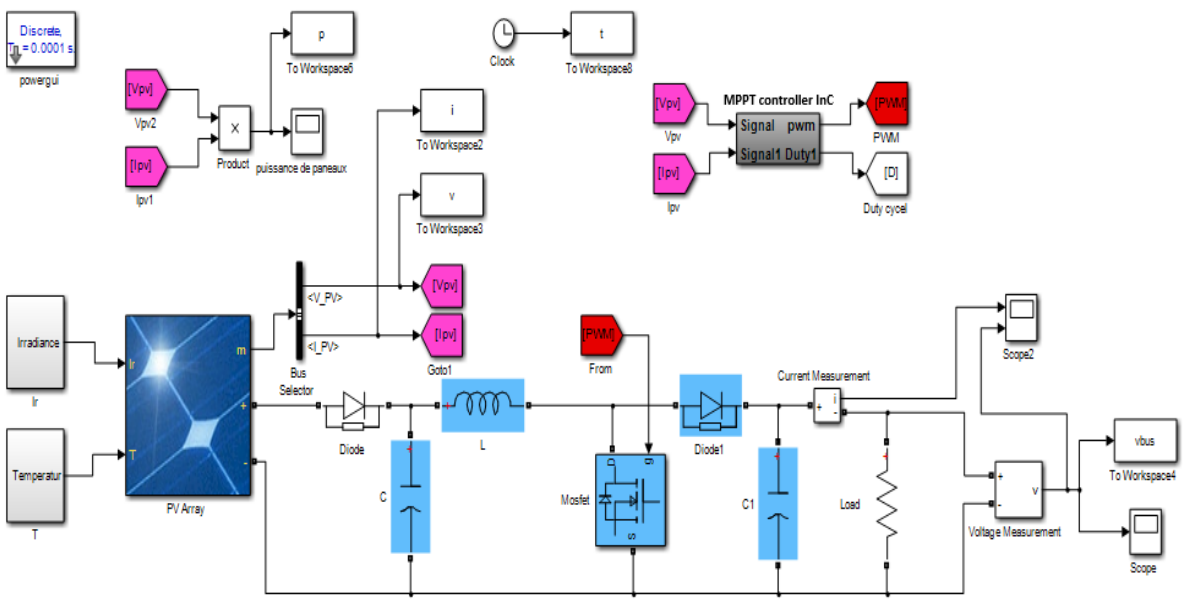

Figure 2.18: Simulink Model of INC MPPT with DC-DC converter.

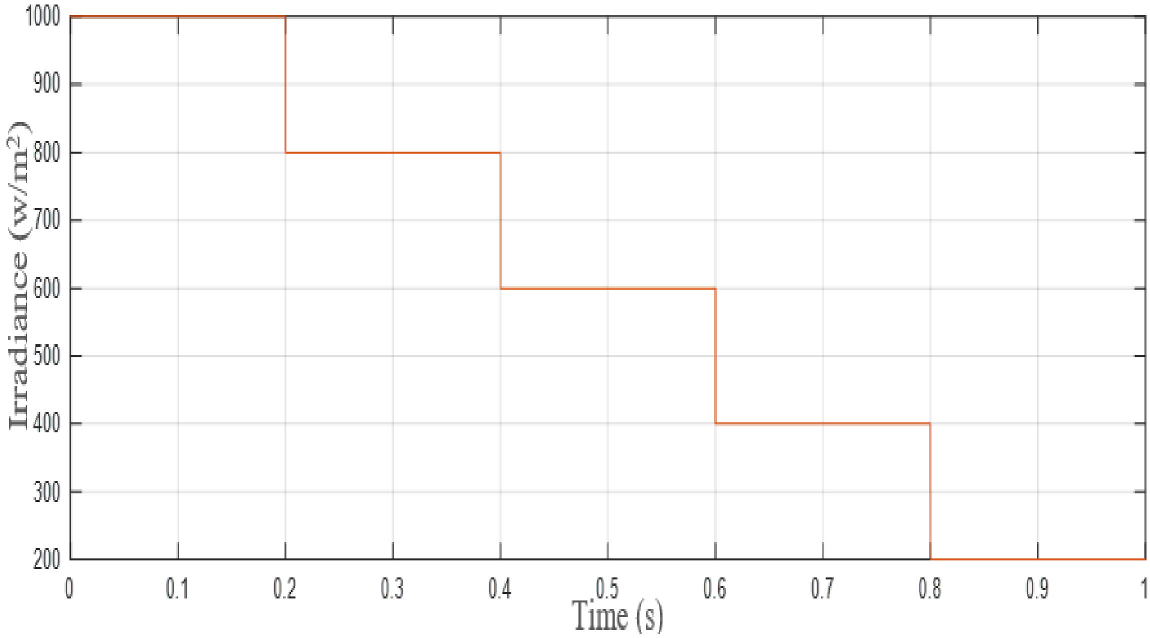

Figure 2.19: Variation of illumination.

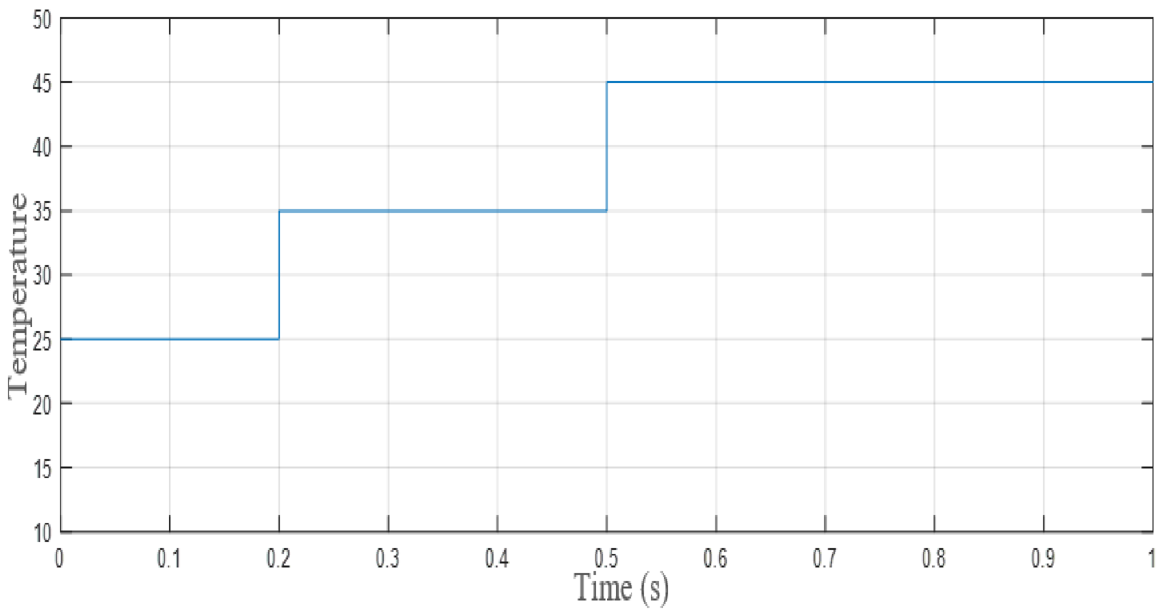

Figure 2.20: Temperature variation.

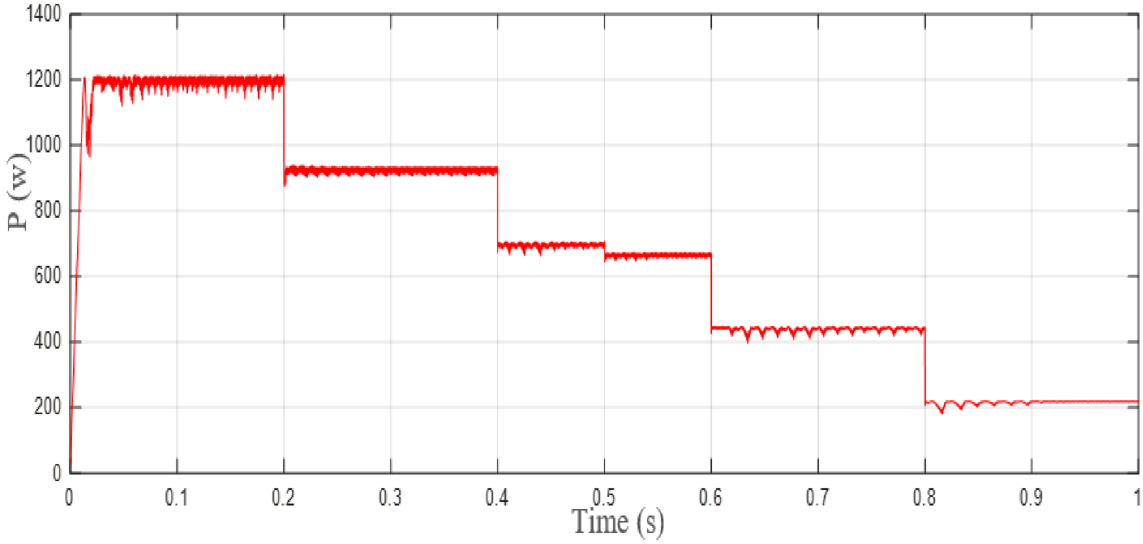

Figure 2.21: P(t) characteristics of a PV system.

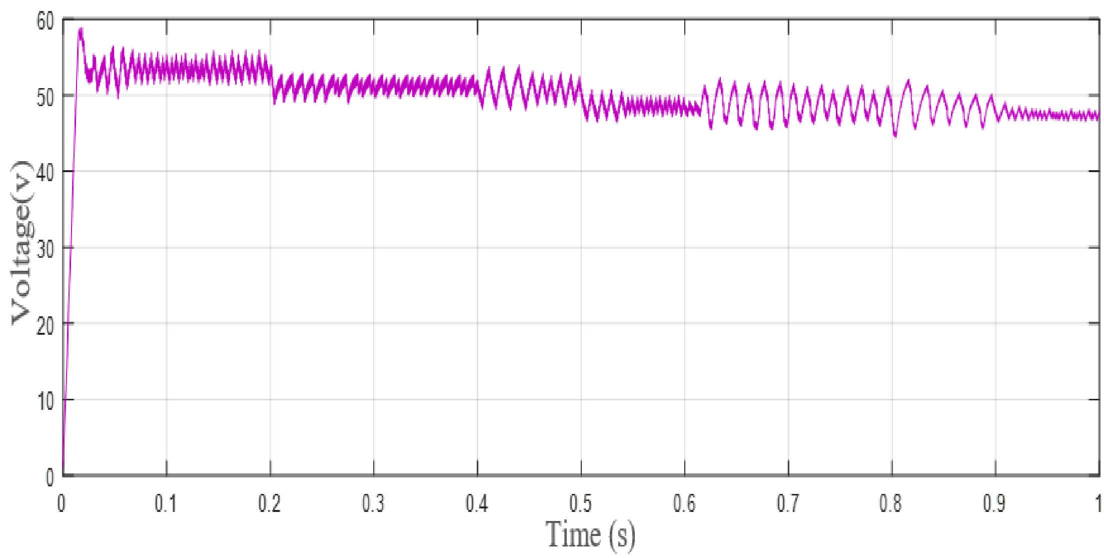

Figure 2.22: V(t) characteristics of a PV system.

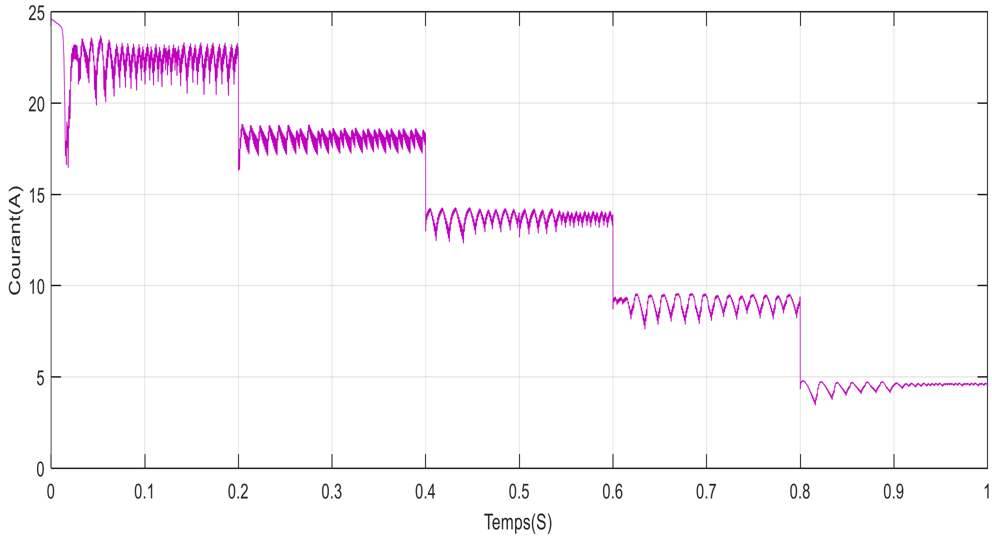

Figure 2.23: Characteristics I(t) of a PV system.

2.7. Conclusion

This chapter presents the modeling and simulation of the assembly consisting of: photovoltaic generator, boost and MPP controls. It forces the GPV generator to work at its maximum power point. The next chapter presents the connection of a PV to the electrical grid with MCS control.

CHAPTER 3: Three Phase Grid Connected Inverter based on Sliding Mode Controller for PV System

3.1. Introduction

Grid-integrated PV systems hold significant promise for sustainable energy production. However, these systems often struggle with maintaining energy quality and stability in the face of fluctuating conditions. To address these challenges, this study proposes the use of SMC for grid-connected PV systems. The system comprises solar panel arrays, a DC-DC boost converter with its controller, and a three-phase inverter integrated into the utility grid.

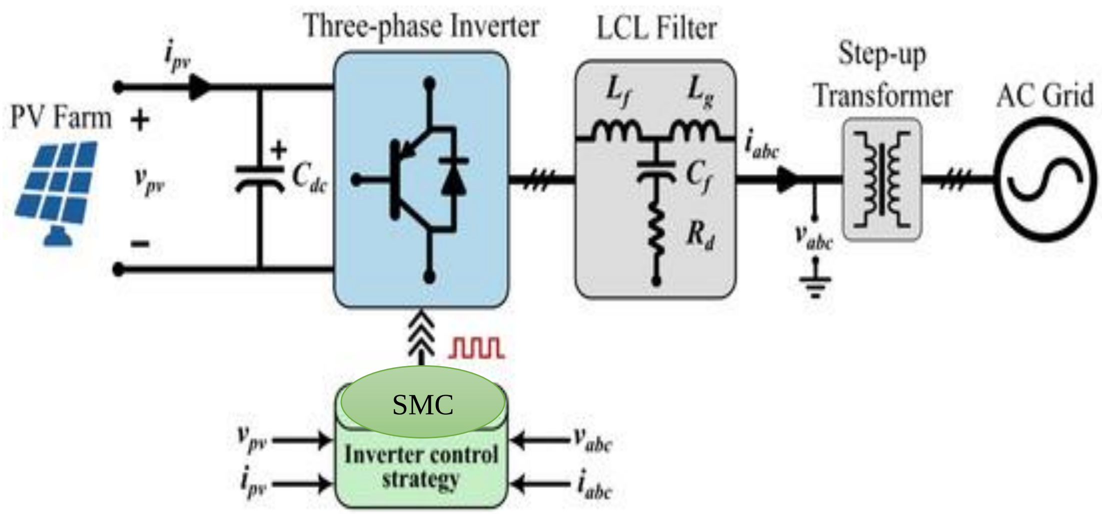

Figure 3.1: The architecture of a three-phase PV system interconnected with the grid.

3.2. Control scheme of a pq-controlled inverter

The control scheme of a PQ-controlled inverter can be seen in Figure 3.1 Aspects of the control scheme were brought in from papers [24], [25], and [26]. It starts off with measurements of voltage and current with the voltage measurement at the point of common coupling (PCC) and the current at the input of the RL filter. These measurements are then converted into parks transformation to generate the i_{dq0} and the v_{dq0} values with the contribution of the measured angle from the PLL. The v_{d0} and the i_{dq0} values represent the output voltages and currents in the d q reference frame. However, these are needed to generate reference current values that are used as inputs for the PI controllers of the current controller.

The equations for the three-phase balanced grid in d-q can be represented by:

$$u_d = L\frac{di_d}{dt} + Ri_d - \omega Li_q + v_d \tag{17}$$

$$u_q = L\frac{di_q}{dt} + Ri_q + \omega Li_d + v_q \tag{18}$$

For making the system stable in closed-loop control, PI regulator is used in addition to the decoupling control using feedforward voltage as presented in Figure 3.2.

$$u_d = -\left(\frac{K_p s + K_i}{s}\right)(idref - i_d) + \omega L i_q + v_d \tag{19}$$

$$u_q = -\left(\frac{K_p s + K_i}{s}\right)(iqref - i_q) - \omega L i_d + v_q \tag{20}$$

Active and Reactive Power Equations.

The instantaneous active and reactive power of three-phase grid-connected inverter can be realized using d-axis and q-axis voltages and currents using following equations:

The separate control of the active and reactive power can be achieved by realizing either v_d or v_q equals to zero.

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \tag{21}$$

$$Q = \frac{3}{2}(v_q i_q - v_d i_d) \tag{22}$$

If $v_d = 0$, will result into the independent control of the active power and reactive power using d-axis and q-axis current control.

$$P = \frac{3}{2} v_d i_d \tag{23}$$

$$Q = -\frac{3}{2} v_d i_q \tag{24}$$

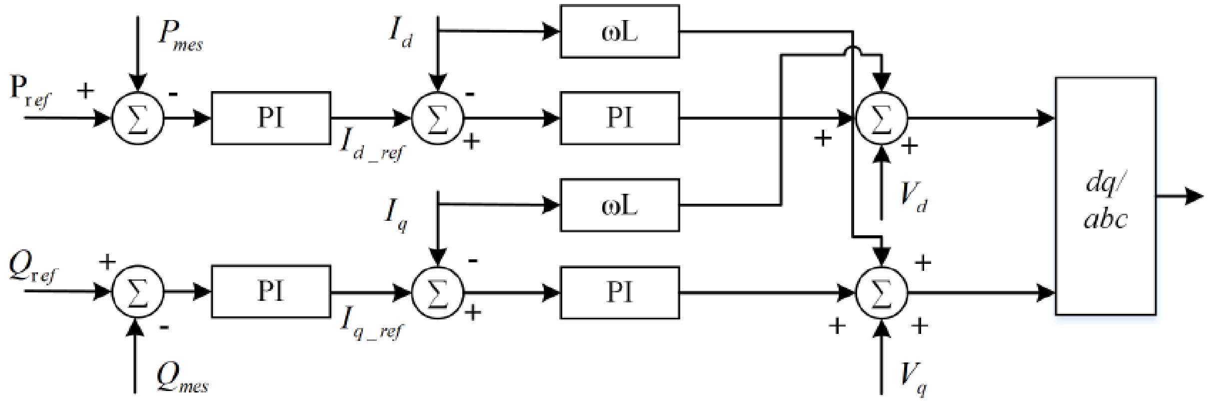

Figure 3.2: active and reactive power of three-phase grid-connected inverter controller.

3.3. Inverter

The inverter converts the DC output from the DC-DC converter to three phase AC to be fed to the grid. The Figure.3.3 shows the block of the three-phase inverter block.

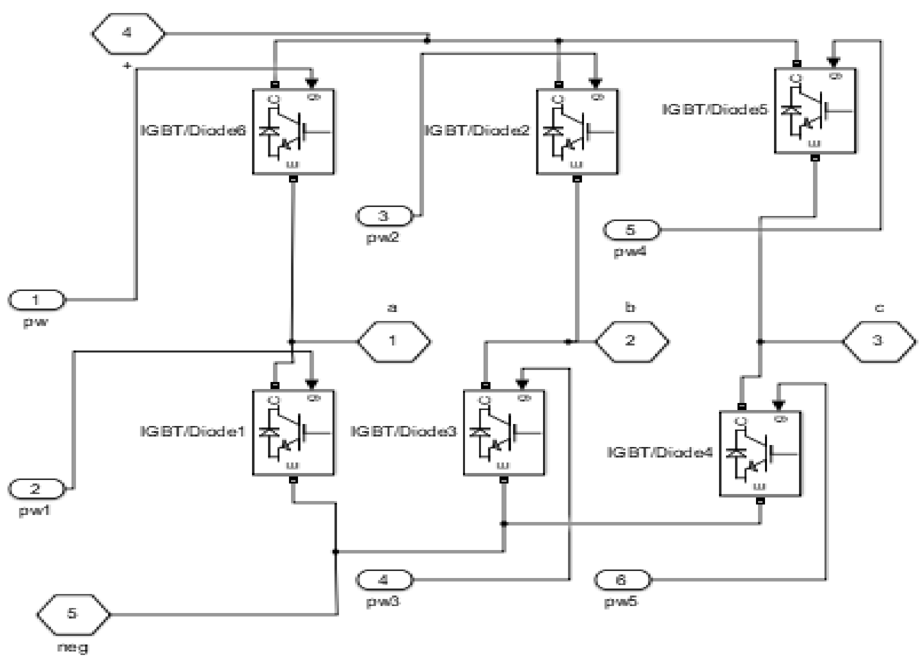

Figure 3.3: Switching block of the inverter.

3.4. Phase Locked Loop (PLL)

Under ideal grid conditions, the determined phase angle (θ) is equal to the phase angle of the grid (ωt) and as can be seen from the following equations; while v_q is equal to zero. It is mandatory to assume that PLL is in locked mode during PLL design which means input signal and feedback signal are in phase and same frequency. When PLL angle is close to instantaneous voltage vector angle.

3.5. Grid Filter

We cannot feed the inverter output directly to the grid due to high quantity of harmonics present in it. The high frequency switches of the inverter introduce harmonics in multiples of the switching frequency. Therefore, it must be conditioned using a filter that can reduce the harmonic content to an acceptable limit.

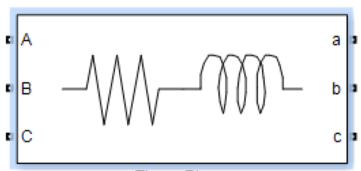

Figure 3.4: RL Filter Topologies.

3.6. Control Design of Sliding Mode:

The controller structure has two parts, one represents the dynamics during the sliding mode and the other represents the discontinuous system dynamics during the convergence mode. The design of the control can be obtained in three important steps and each step is dependent on another one:

• The choice of surface.

$$S(x) = \left(\frac{\partial}{\partial x} + \lambda_x\right)^{r-1} e(x) \tag{25}$$

is the difference between the controlled variable x and its reference

$$e(x) = x_{ref} - x \tag{26}$$

The nonlinear form is a function of the error on the controlled variable (x), it is given by

The structure of a sliding mode controller consists of two parts. The first one concerns the exact linearization u_{eq} and the second one concerns the stabilization $u = ueq - un$

where u_{eq} corresponds to the control. It serves to maintain the variable control on the sliding surface unis the discrete control determined to check the convergence condition

The system can be written in two sets of state equations

$$\begin{cases} V_{od} = Ri_{Id} + L\frac{di_{Id}}{i_{Id}} - L\omega_s i_{Iq} + V_{rd} \\ V_{oq} = Ri_{Iq} + L\frac{di_{Iq}}{i_{Iq}} + L\omega_s i_{Id} + V_{rq} \end{cases} \tag{27}$$

$$\begin{cases} V_{od-ref} = V_{Id-ref} - L\omega_s i_{Iq} + V_{rd} \\ V_{oq-ref} = V_{Iq-ref} + L\omega_s i_{Id} + V_{rq} \end{cases} \tag{28}$$

The output is the vector of currents $I_l = [i_{ld} i_{lq}]^T$ S_1 et S_2 constituent are respectively the sliding surfaces of the output variables i_{ld} et i_{lq}

respectively, representing direct and quadratic current errors.

We select the sliding surface as:

$$\begin{cases} S_1 = i_{ld-ref} - i_{ld} \\ S_2 = i_{lq-ref} - i_{lq} \end{cases} \tag{29}$$

discrete control is as follows: un=k sing(S)

Using the equations of system (03), the first derivation of Eq. 04 gives

$$:\begin{cases} S_1' = i_{ld-ref}' + \frac{1}{L}[R_{ild} - L\omega_s i_{lq} + V_{\ rd}] - \frac{1}{L}V_{od} \\ S_2' = i_{lq-ref}' + \frac{1}{L}[R_{ilq} - L\omega_s i_{ld} + V_{\ rq}] - \frac{1}{L}V_{oq} \end{cases} \tag{30}$$

The relative degree of the system is equal to 1, as the control appears in the first derivation of the variables to be controlled .

The solution of the equation $S'= 0$ leads to the controller equivalent (U_{eq}). Its expression is given by:

$$\begin{aligned} i_{ld-ref}' &= \frac{1}{L}[R_{ild} - L\omega_s i_{lq} + V_{\ rd} - V_{od}] \\ i_{lq-ref}' &= \frac{1}{L}[R_{ilq} - L\omega_s i_{ld} + V_{\ rq} - V_{oq}] \end{aligned} \tag{31}$$

The non-linear part of the sliding controller is given by:

$$\begin{cases} i_{ld-nl} = K_d singS_1 \\ i_{lq-nl} = K_q singS_2 \end{cases} \quad (32)$$

where, k_d, and k_q are proportional gains of the equivalent command the command of two level three phase inverter is described as follows terms:

$$\begin{cases} i_{ld} = i'_{ld-ref} + K_d singS_1 \\ i_{lq} = i'_{lq-ref} + K_q singS_2 \end{cases} \quad (33)$$

With zero reactive power, the current in the Park reference frame on the q axis = 0

Therefore, set the direct current component equal to zero. $I_q = 0$. The sliding mode control diagram is as follows:

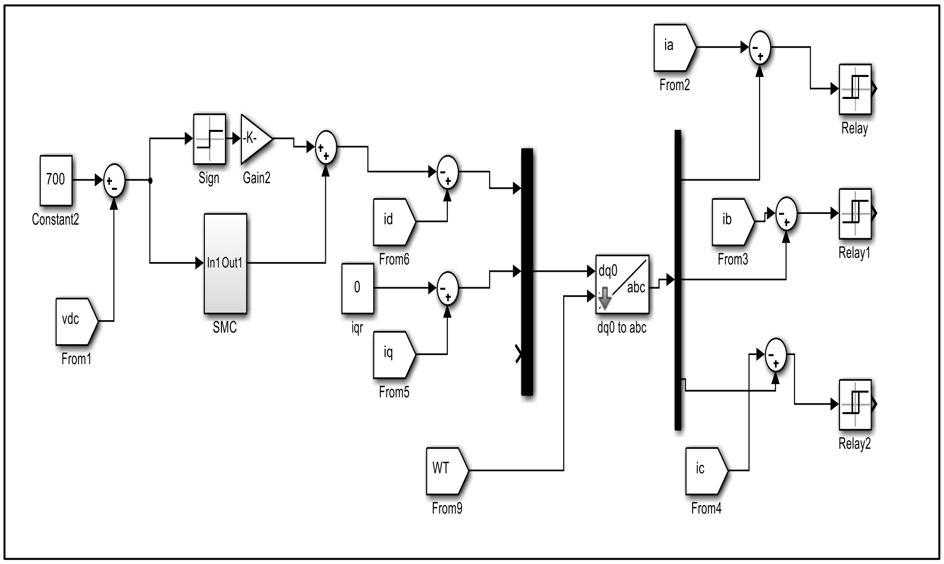

Figure 3.5: Inverter sliding mode controller Block.

The hysteresis controller is used to generate switching signals to control inverter switches to force the desired current into the system.

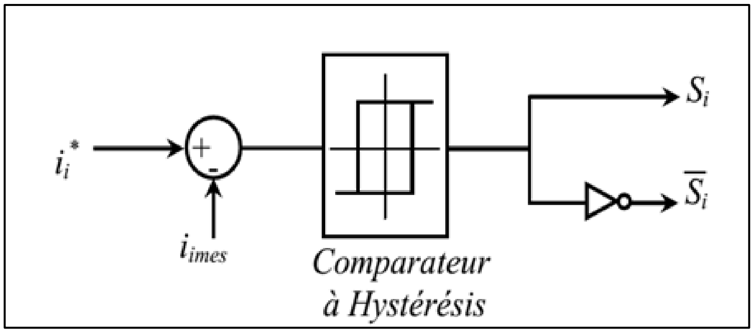

Figure 3.6: two level hysteresis current controls.

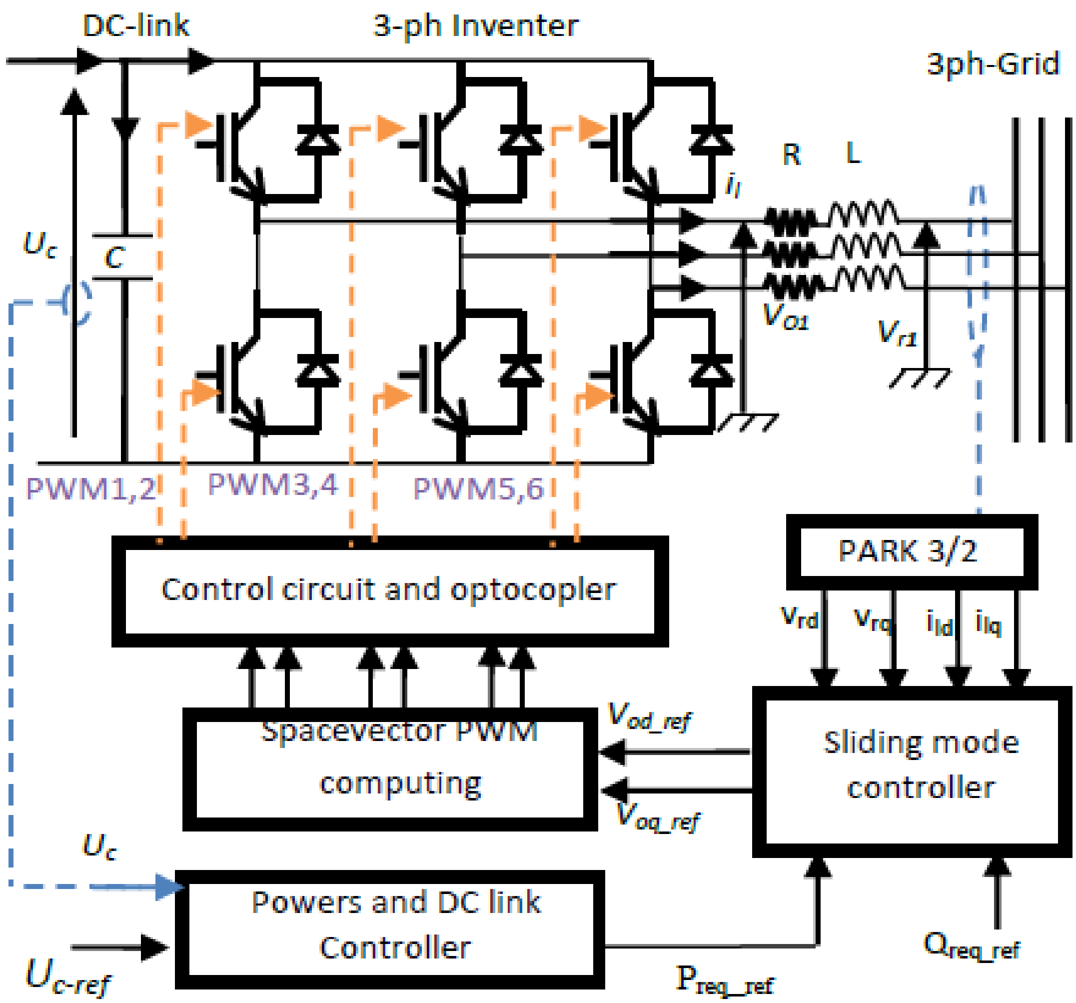

Figure 3.7: Control structure of grid-connected PV inverter.

3.7. Simulation Setup

The simulation was carried out using MATLAB/Simulink environment to evaluate the performance of the proposed control strategy. PV system was modeled based on standard solar panel parameters, and the MPPT algorithm was implemented using a SMC.

Parameters of the PV grid connected inverter

PV array power	4 kW
Inductance of the boost	0.1mH
DC-link capacitance	3mF
Filter resistance Rf	0.16Ω
Filter inductance Lf	0.1mH
grid-frequency	50 Hz
Grid line-line voltage u0	400 V
sampling time TS	40µS

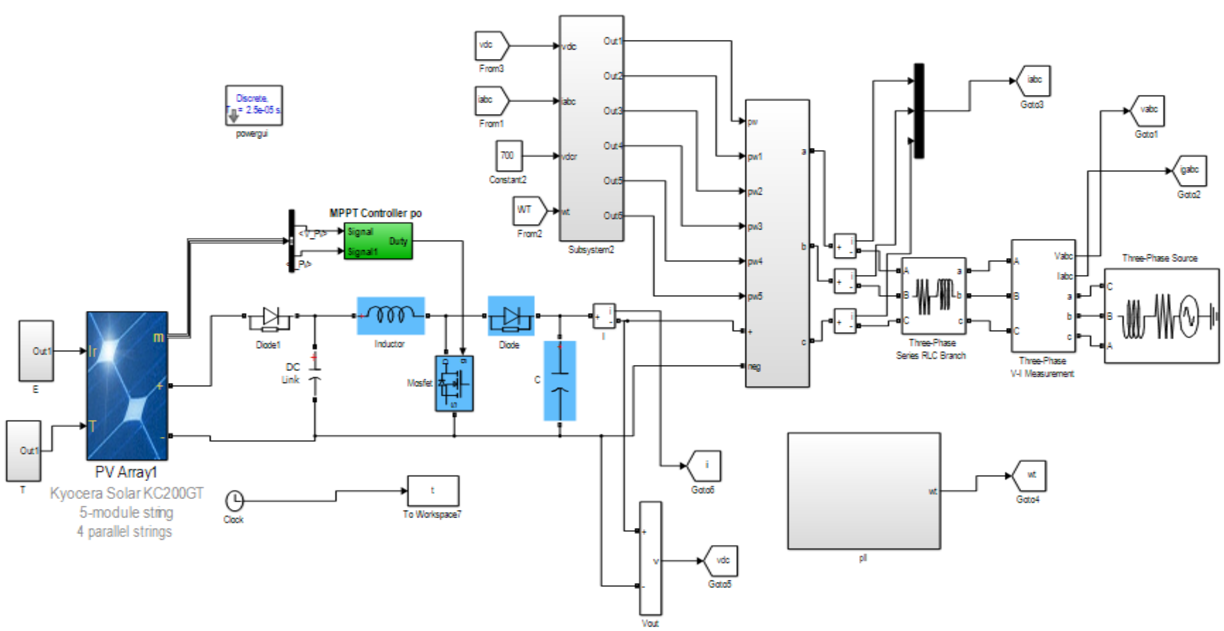

Figure 3.8: Simulated power circuit of proposed PV-grid system

3.7.1. Simulation results

The simulation implemented a simplified version of the proposed scheme. A DC source was used instead of the generalized model of a PV array. Topology presented in figure 3.8 shows a 3-phase inverter used as the DC-AC convertor. The PLL block takes feedback from the grid is to track the phase angle required for abc to dq transformation.

We make application under MATLAB/Simulink and we present simulation results under the following operating conditions: Irradiance level G is changed from 1000 to 200 W/m2 and temperature Tj is changed from 25 to 45C.

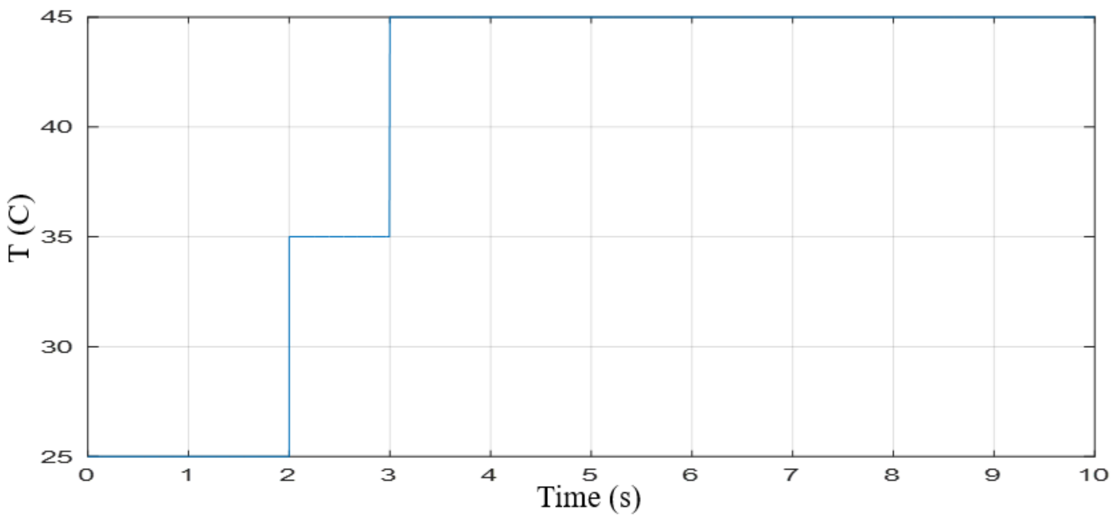

Figure 3.9: temperature changes subject to PV array.

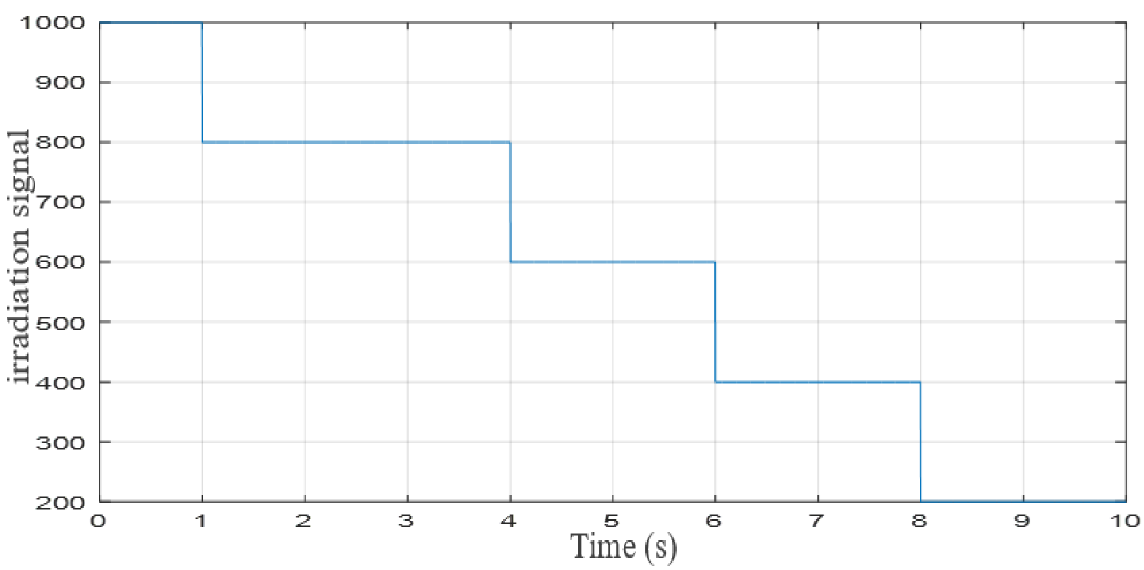

Figure 3.10: varying irradiation.

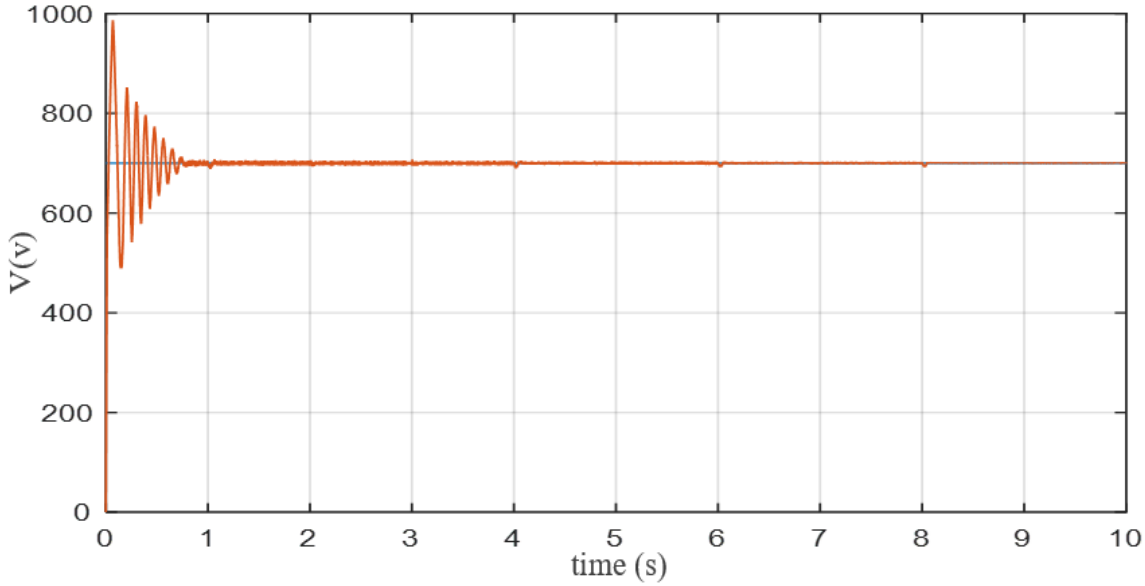

Figure 3.11: Reference and voltage across the capacitor of inverter input.

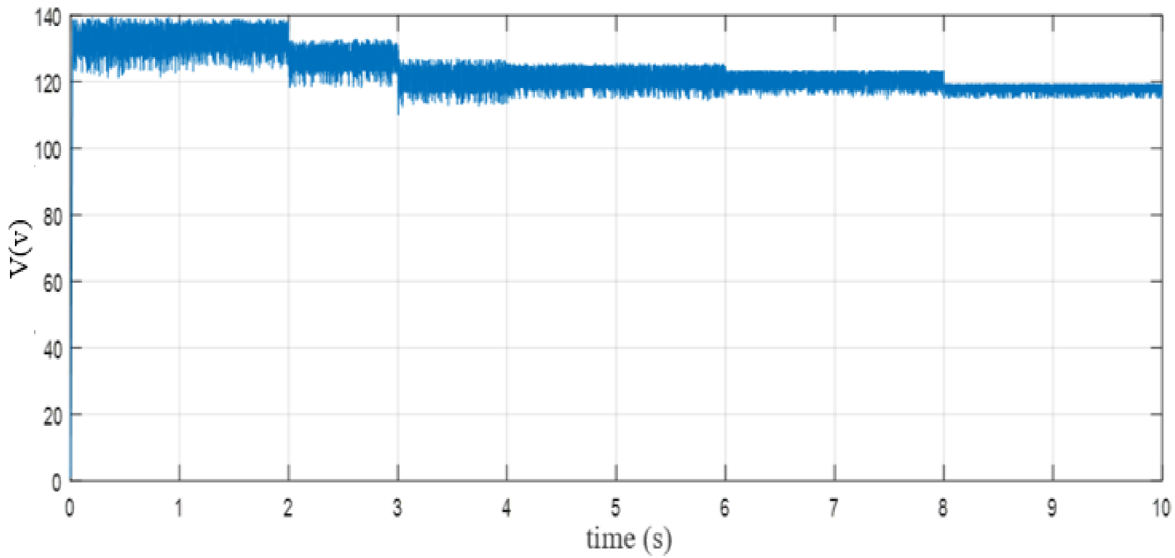

Figure 3.12: output voltage of PV array.

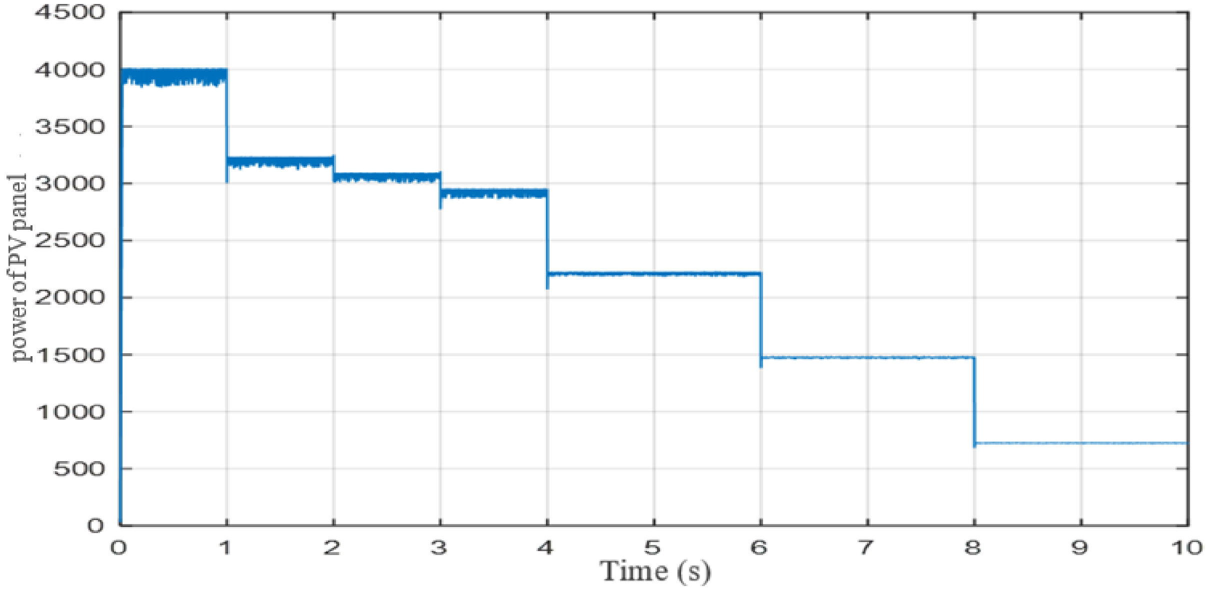

Figure 3.13: Power generated by PV.

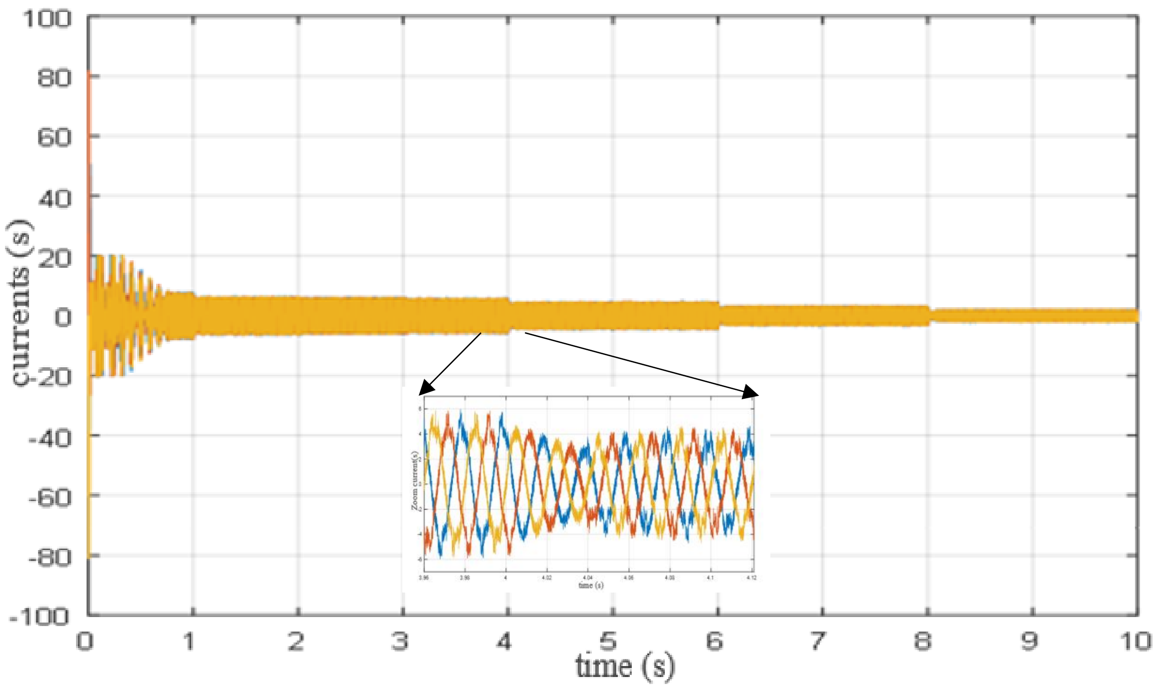

Figure 3.14: Three-phase current at the inverter output with zoom portion

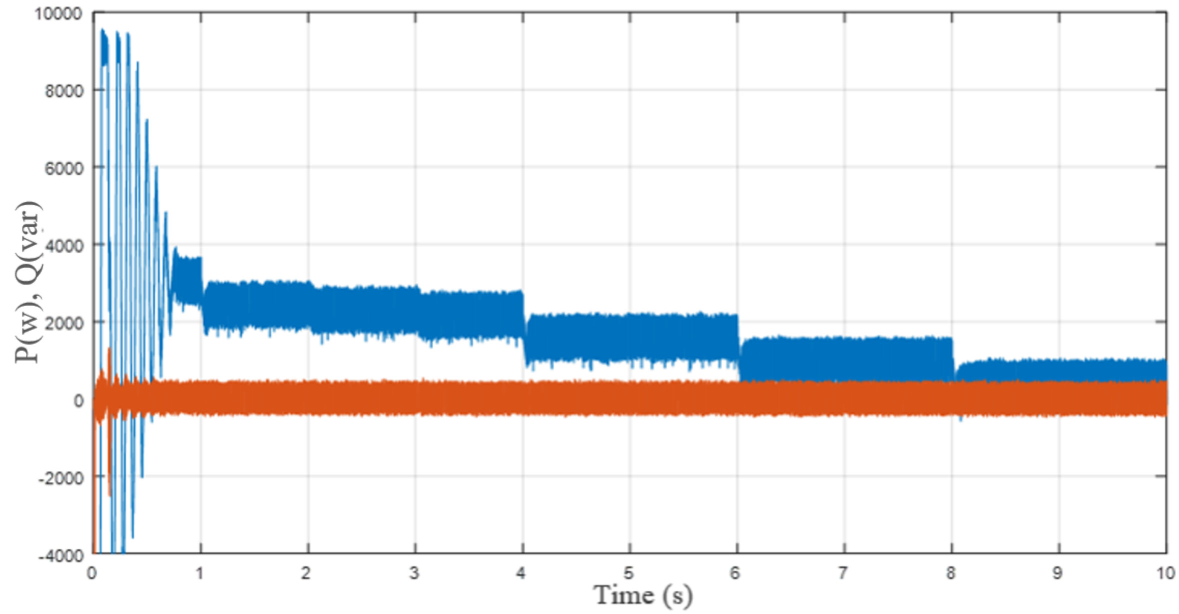

Figure 3.15: The active power and reactive power.

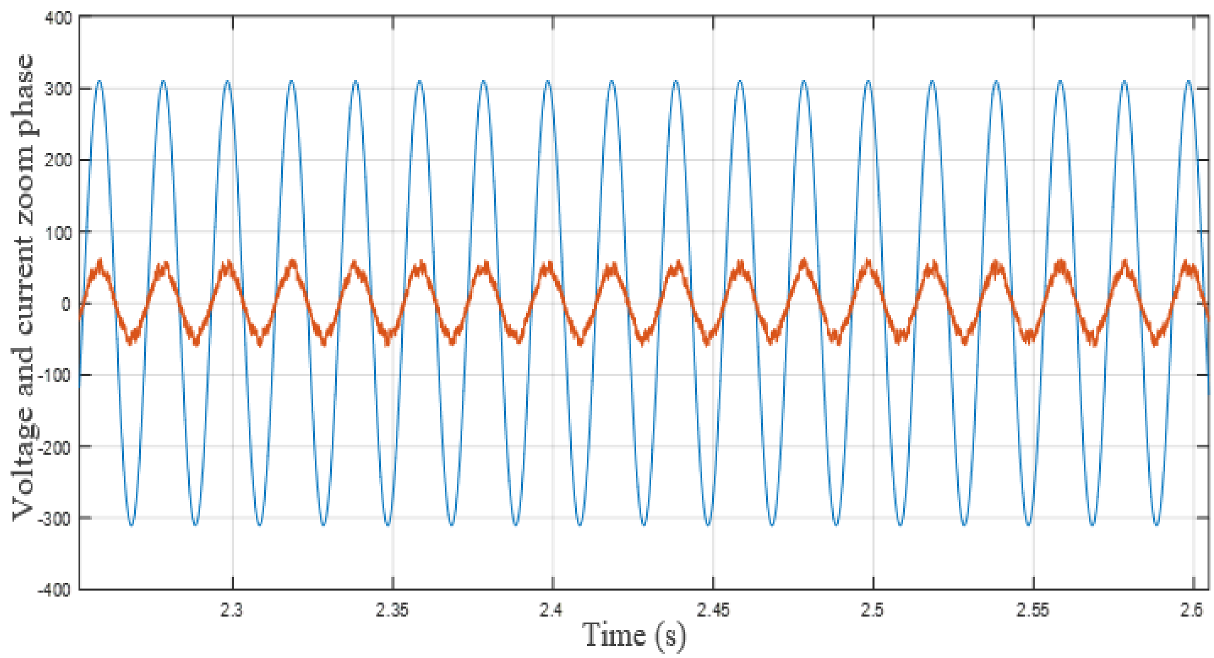

Figure 3.16: Zoom portion of current at the inverter output.

3.8. Conclusion:

This work displays the control performance of PV grid connected by utilizing a SMC approach. Approvals performed by reproduction in MATLAB/Simulink have demonstrated the adequacy of the studied methodologies for the control of the power converters based on SMC controller. From these findings, we can say clearly that the studied control technique drew a tremendous amount of interest result to its advantages such as robustness and low harmonic distortion. Future investigations will be held on this technique.

General Conclusion

In this study, has presented the control performance of a grid-connected PV system using the SMC technique. The objective was to ensure that the PV system operates efficiently while maintaining grid stability and maximizing power extraction from the solar array. By implementing the control strategy in MATLAB/Simulink, we simulated various operational scenarios to test the effectiveness of the approach under different environmental and load conditions.

The simulation results confirmed that the SMC-based controller offers superior performance compared to conventional control methods. One of the key advantages observed is its strong robustness against parameter variations and external disturbances. The controller was able to maintain stable operation of the power converters, track the MPP efficiently, and regulate grid injection with minimal error.

Furthermore, the use of SMC significantly contributed to reducing harmonic distortion in the output signals, ensuring better power quality when interfacing with the utility grid. This low Total Harmonic Distortion is crucial for complying with grid codes and protecting sensitive equipment connected to the network. Additionally, the dynamic response of the system under SMC control was fast and smooth, showing adaptability to sudden changes in irradiance or load.

In conclusion, the studied SMC technique has demonstrated promising potential in enhancing the performance of grid-connected PV systems. Its robustness, precision, and power quality benefits make it a strong candidate for future PV control implementations. Further research will aim to test this approach experimentally and explore its integration into larger-scale systems, including microgrids and hybrid renewable energy systems.

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