الجمهورية الجزائرية الديمقراطية الشعبية

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE

وزارة التعليم العالي و البحث العلمي

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

جامعة أبي بكر بلقايد – تلمسان –

Université Aboubakr Belkaïd – Tlemcen –
Faculté de TECHNOLOGIE

MEMOIRE

Présenté pour l'obtention du **diplôme** de **MASTER**

En : Electrotechnique

Spécialité : Commandes Electriques

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Sujet

Comparative Study of Maximum Power Point Tracking Controls Applied to a Photovoltaic System Connected to the Electrical Network

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Année universitaire :2021 /2022

Acknowledgements

First and foremost, we would like to acknowledge through the expression of sincere gratitude to God Almighty for His sustainable grace that has seen us through this work.

To our parents who have been our first teachers and have seen us grow, loved us unconditionally and been with us through every step, we thank you.

We would like to give our special gratitude to our supervisor Mr BOUMEDINE Abdelmadjid for his unending support, guidance, consistent push and encouragement through which our work was completed.

Furthermore, we give our recognition to the members of the jury, the President Madame BENREZZAK Nawel and the examiner Mr MALTI Abed Chaib for taking out of their time to examine and evaluate our work.

Finally, we would like to give our immense appreciation to the entire members Department of Electrical and Electronics Engineering, our professors for being a significant part of our journey up until our masters and an additional special recognition to the secretary Mme ABDELAOUI Amaria for facilitating for a smooth and comfortable learning process through her communication skills, we will surely never forget.

Dedication

This work is a fruit of countless and arduous sacrifices through the researchers' effort. I wholeheartedly dedicate this work to Almighty God who gave me strength, courage and protection, and who kept me healthy during the research process, for that, I'm sincerely and truly grateful.

To my beloved parents as you have been my pillars of strength and inspirational through your continuous moral and emotional support throughout the process.

To my precious brothers, sisters and relatives, as you have been a source of motivation and encouragement till the completion of this work.

To my colleague Mumbi Franchesca, my course mates, my professors and supervisors.

Akinwale Emmanuel

I whole heartedly dedicate this work to my grandfather the late R.M.M Mumbi as he has always been my greatest support through his words, actions, love and sense of passion which lives on even after his death, thank you for being my epitome of peace.

To my late grandmother and auntie Edna Mumbi and Patricia Chilombo Mumbi respectively for being great pillars and support in my life.

To my parents Nigel Mumbi and Beauty Mtonga for their unconditional love, to my auntie Sheila Mumbi for encouraging me in many ways and prompting me to continue with my masters. To my sisters Esther Nayame and Lillian Mana for their unconditional love, to my brothers, sisters, aunties, uncles and friends.

Finally, to my colleague Emmanuel Kayode Akinwale

Franchesca Mumbi

Abstract

With the ever-increasing energy demand worldwide coupled with the possibility of reduced supply of conventional fuels (gas, coal and oil), along with growing concerns about environmental preservation and its finite sources, has driven research and development of alternative energy sources that are cleaner, greener and renewable with little environmental impact. Among the alternative sources, the electrical energy from PV system can be regarded as more useful with unlimited potential. Since it is free, abundant, clean, and found all around the globe. It is estimated that solar energy reaching the earth's surface from the sun is of the order of ten thousand times greater than the world's energy consumption. According to experts and also looking at current global trends, PV energy will become the most important renewable energy source in the nearest future, accounting for almost 28% off all world energy consumed. In this context, the concept of energy generation from solar energy, becomes a real and present technical possibility, this in turn has caused various researches on its usage around the world.

Despite all the advantages presented by the generation of energy through the use of PVs, the efficiency of energy conversion is currently low and the initial cost for its implementation is still considered high. One of the ways to overcome this challenge is to use techniques to extract the maximum power from these solar panels, in order to achieve maximum efficiency in operation. It should be noted that there is only one point of maximum power (MPP - Maximum Power Point), and this varies according to climatic conditions. The photovoltaic power characteristics is nonlinear. It also varies with the level of solar irradiation and temperature, which make the extraction of maximum power a complex task. To overcome this problem, several methods for extracting the maximum power have been proposed in this project and a careful comparison of these methods can result in important information for the design of these systems. Therefore, this project aims to assess some of the main MPPT techniques using models in MATLAB/Simulink.

Keywords:
Photovoltaic Systems, MPPT, Renewable energy, Grid-connected PV system, Energy generation

Résumé

Avec la demande énergétique mondiale sans cesse croissante associée à la possibilité d'une réduction de l'offre de combustibles conventionnels (gaz, charbon et pétrole), ainsi que les préoccupations croissantes concernant la préservation de l'environnement et ses sources limitées, a conduit la recherche et le développement de sources d'énergie alternatives qui sont plus propres, plus vertes et renouvelables avec peu d'impact sur l'environnement. Parmi les sources alternatives, l'énergie électrique du système PV peut être considérée comme plus utile avec un potentiel illimité. Puisqu’elle est gratuite, abondante, propre et trouvée partout dans le monde. On estime que l'énergie solaire atteignant la surface de la terre depuis le soleil est de l'ordre de dix mille fois supérieure à la consommation énergétique mondiale. Selon les experts et en examinant également les tendances mondiales actuelles, l'énergie PV deviendra la source d'énergie renouvelable la plus importante dans un avenir proche, représentant près de 28 % de toute l'énergie mondiale consommée. Dans ce contexte, le concept de production d'énergie à partir de l'énergie solaire devient une possibilité technique réelle et actuelle, ce qui a à son tour suscité diverses recherches sur son utilisation dans le monde entier.

Malgré tous les avantages présentés par la génération d'énergie par l'utilisation des PV, l'efficacité de la conversion d'énergie est actuellement faible et le coût initial de sa mise en œuvre est toujours considéré comme élevé. L'un des moyens de surmonter ce défi consiste à utiliser des techniques pour extraire le maximum de puissance de ces panneaux solaires, afin d'atteindre une efficacité de fonctionnement maximale. Il est à noter qu'il n'existe qu'un seul point de puissance maximale (MPP - Maximum Power Point), et celui-ci varie en fonction des conditions climatiques. La caractéristique de puissance photovoltaïque est non linéaire. Elle varie également avec le niveau d'irradiation solaire et la température, ce qui rend l'extraction de la puissance maximale une tâche complexe. Pour surmonter ce problème, plusieurs méthodes d'extraction de la puissance maximale ont été proposées dans ce projet et une comparaison minutieuse de ces méthodes peut donner des informations importantes pour la conception de ces systèmes. Par conséquent, ce projet vise à évaluer certaines des principales techniques MPPT à l'aide de modèles dans MATLAB/Simulink.

Mots Clés :

Systèmes photovoltaïques, MPPT, Énergie renouvelable, Système PV connecté au réseau, Production d'énergie

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Abbreviations and Nomenclature

AC	Alternating Current
AM	Air Mass
ANN	Artificial Neural Network
AU	Astronomical unit
CO_2	Carbon Dioxide
CSP	Concentrating Solar Power
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DIF	Diffused Horizontal Irradiation
DNI	Direct Normal Irradiance
DSC	Dye-sensitised Solar Cell
FF	Fill Factor
FL	Fuzzy logic
GCPV	Grid Connected Photovoltaic
GHGs	Green House Gases
GHI	Global Horizontal Irradiation
GNI	Global Normal Irradiance
IEC	International Electrotechnical Commission
KCL	Kirchhoff’s Current Law
KVL	Kirchhoff’s Voltage Law
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PERC	Passivated Emitter and Rear Cell
PSH	Peak Sun Hours
PSO	Particle Swarm Optimisation
PV	Photovoltaic
PVT	Photovoltaic thermal
PWM	Pulse Width Modulation
STC	Standard Test Conditions
TSI	Total Sun Irradiance
WSPVs	Wavelength-Selective Photovoltaic Systems

Symbols

H	Insolation
G	Irradiance
eV	electron volt
h	Planck’s Constant
v	photon frequency
w_i	work out
GaAs	gallium arsenide
Si	silicon
β	positive constant
r	relative degree
Rs	series resistance
Rsh	shunt resistance
Is	current
Vs	voltage
T	temperature
$\mathrm{I_{ph}}$	photocurrent
$\mathrm{I_d}$	current
N_s	Total number of cells in series
R_p	Parallel Resistance
K	Boltzmann constant
Io	reverse saturation current of diode
n	diode ideality factor
q	electron charges
G	Solar Irradiation
E_g	Band gap energy of the semiconductor

GENERAL INTRODUCTION

General Introduction

Photovoltaic systems are systems that convert sunlight from the sun into electricity through the use of photovoltaic effect. This is a process in which semiconducting materials generate voltage and current, and thus electricity when exposed to light. For applications in real life, this effect is usually implemented with the aid of solar cells which are individual devices whose electrical characteristics vary when exposed to light. These cells are usually made out of polycrystalline or monocrystalline silicon and can be connected in series or parallel to achieve the desired voltage and current respectively. These cells generate electricity when photons of light hit the solar panel and then knock electrons in the substrate material into a higher level of activity; these electrons are then channelled off of the panel to create DC electricity. As such, solar panels can be used to generate electricity used in powering homes, schools, clinics and other remote places or areas which are isolated from the grid (Off-grid PV systems) as found in Off-grid systems or connected to grid. In this master's thesis we'll be focusing more on grid-connected PV system [1][66].

Grid-connected photovoltaic (PV) systems are increasingly attracting the attention of industry and academia as a means of providing an alternative to conventional fossil-fuel generation due to its nature as a clean source of electricity generation and the availability of solar energy in abundance in most countries.

In grid-connected PV systems, a key consideration is the design and operation of power converters and how to achieve high efficiency for different power configurations. The requirements for converter connection include: maximum power point, high efficiency, control power injected into the grid, and low total harmonic distortion of the currents injected into the grid. Consequently, the performance, efficiency and power of our PV system connected to the grid depends largely on the control strategy applied. Which leads us to compare different MPPT control algorithm.

The main aim of this research work is to:

- ✓ Model then simulate an ideal PV panel and a single diode model of a real solar panel, find a MATLAB equivalent of our models then compare PV and IV characteristic of our models to real life characteristics given by the manufacturer.
- ✓ Model and simulate a DC/DC boost converter connected to a resistive load with a constant duty cycle to test our converter. Perturb and Observe, Incremental conductance MPPT control strategy is then applied to our system for comparison.

- ✓ Finally, a 3-level bridge inverter is then used to convert our DC to AC before being connected to grid and then we compare the efficiency and power of us our various MPPT control strategy.

This master’s thesis is divided into six (6) chapters.

Chapter I: This chapter is focused on introducing the generalities of solar renewable energy and its constantly increasing demand globally. We discussed global solar potential, and the various types of solar Irradiance. This chapter also contains a discussion on solar potential in African countries while placing prominence on countries like Algeria, Zambia, and Nigeria.

Chapter II: This chapter is dedicated to the photovoltaic systems, that is to say, the history surrounding the development of solar panels including a discussion of semiconductors and PV hierarchy. We illuminated the operation principles of the PV system, its usefulness as well as efficiency. Furthermore, we explored the different types, components, and technologies of a PV system. Finally, we reviewed the advantages and disadvantages of this system.

Chapter III: This chapter presents the settings, modeling, and simulation of the PV system. With the application of mathematical equations and MATLAB/Simulink, we modeled three different PV cells the Ideal PV cell, the Single diode model, and the Double diode model as well as analyzed the application of Newton Raphson for the resolution of nonlinear equations. We concluded this chapter by studying the different simulated characteristics of the PV cells with constant/varying Temperature as well as constant/varying Irradiance.

Chapter IV: This chapter is consecrated to DC-DC converters and Topologies focusing mainly on Buck, Boost, and Buck-Boost. We discussed their modes of operation and use, thereafter concluded with the analysis of the simulation of the PV array connected to the Boost converter.

Chapter V: This chapter is devoted to the application of Maximum Power Point Trackers (MPPT). In this chapter, we discussed MPPT controls, in particular, P&O, Incremental conductance, and sliding mode, how they are used as well as their modeling in MATLAB/Simulink using Algorithms and Mathematical equations. We concluded this chapter by analyzing and comparing the simulations of the characteristics of a PV cell connected to the MMPT controls.

Chapter VI: Our final chapter is dedicated to the global simulation of the PV system connected to the grid. In this chapter, we discussed DC-AC converters and their importance to the

Photovoltaic system in particular we discussed the PV cell connected to a Grid-connected Three-Phase inverter. We discussed some of the controls needed to generate the inverter and finally, we concluded this chapter with the global simulation of the PV system connected to the grid and resistive load for our applied MMPT controls. To conclude our work in this thesis, we therefore, gave our general analysis and conclusion on the system.

Problematic and Motivation of Study

With the world’s transition towards cleaner and greener forms of electricity generation, solar energy has been focused on more and more. Solar energy is one of the least efficient forms of energy generation. A good command strategy will go a long way in increasing the efficiency. By comparing different MPPT algorithm for our MPP we can choose the better and most applicable control strategy.

With the dearth of energy in Nigeria, Zambia and most African countries in general, solar energy provides a way to fill this dearth. Africa is blessed with abundant sunlight therefore, an investment in grid-connected PV system of generating power from solar energy can significantly improve and address some of the energy problems being faced by African countries. The desire to see an improvement of the lives of people through the provision of safe, clean and stable source energy in Africa is the motivation behind this project.

CHAPTER1

INTRODUCTION AND GENERALITIES

1.1. SOLAR ENERGY

The need for energy demands is constantly increasing globally, while stocks from conventional energy sources are finite. Locating and exploiting new sources of conventional energy is becoming increasingly difficult due to the unknown quantities of coal, oil, and gas reserves and their expensive and dangerous way of extraction. In addition to the energy crisis, global warming, resulting in the potential threat of global climate change, is mainly due to Green House Gases (GHGs) mainly from CO_2 emitted from fossil fuel consumption emissions, but also from other gases contributing to greenhouse effect. Climate change causes several negative effects on nature and humans. Due to these reasons; an environmentally friendly and clean energy with an abundance source, which is easily found and exploited is needed. This leads us to solar energy which is the energy gotten from the sun.[48]

The amount of sunlight that strikes the earth's surface in an hour and a half is enough to handle the entire world's energy consumption for a full year. Solar technologies convert sunlight into electrical energy either through photovoltaic (PV) panels or through mirrors that concentrate solar radiation. This energy can be used to generate electricity or be stored in batteries or thermal storage.[64]

Solar energy technologies harness the energy of solar irradiance to produce electricity. Currently, there are principally two technologies employed:

- photovoltaics (PV): PV generates electricity using the conducting properties of certain chemicals most importantly silicon, through the photo-electric effect
- concentrating solar power (CSP) technologies: CSP makes use of reflectors to focus sunlight on a small area, in order to generate steam that powers a thermal electric plant

Other solar technologies include

- Passive Solar Technology: Provides light and harnesses heat from the sun to warm our homes and businesses in winter
- Solar Water Heating: Harnesses heat from the sun to provide hot water for homes and businesses.
- Solar Process Heat: Uses solar energy to heat or cool commercial and industrial buildings.

In addition to electricity generation, solar power is employed to produce thermal energy (heating or cooling, either through passive or active means), to meet direct lighting needs and, potentially, to produce fuels that might be used for transport and other purposes.

1.2. Solar Irradiance

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation as measured in the wavelength range of the measuring instrument. The solar irradiance is measured in watt per square metre (W/m^2) in SI units. Solar irradiance is often integrated over a given time period in order to report the radiant energy emitted into the surrounding environment (joule per square metre, J/m^2) during that time period. This integrated solar irradiance is called solar irradiation, solar exposure, solar insolation, or insolation.

Irradiance may be measured in space or at the Earth's surface after atmospheric absorption and scattering. Irradiance in space is a function of distance from the Sun, the solar cycle, and cross-cycle changes. Irradiance on the Earth's surface additionally depends on the tilt of the measuring surface, the height of the sun above the horizon, and atmospheric conditions. Solar irradiance affects the amount of energy we can get from the sun through a PV panel. It also affects plant metabolism and animal behaviour.

When dealing with photovoltaic solar panels purely for the generation of solar power, a solar irradiance light level of 1.0 kW/m^2 is known as one “Full Sun”, or commonly “Peak Sun”. The definition of “Peak Sun Hours” (PSH) is therefore the number of hours in time that this full sun solar irradiance light level was received at the panels surface at a measurement of 1.0 kW/m^2.

However, when the solar radiation is averaged over the entire 24-hour day and night cycle as well as over a whole year of 365 days, even the best locations receive on average per day only 250–300 W/m^2. That’s less than 30% of what arrives at the top of the Earth’s atmosphere. So, there is a lot of what is called “solar attenuation”, that is the loss of solar irradiance, as it passes through the Earth’s atmosphere before it reaches the Earth’s surface with solar attenuation being greater during the winter months.

We could plot the daily, monthly or even annual amounts of solar irradiance (power) available for any given location giving us a clearer idea of the minimum and maximum levels available for the generation of electrical energy using photovoltaic panels as shown in figure 1.1.

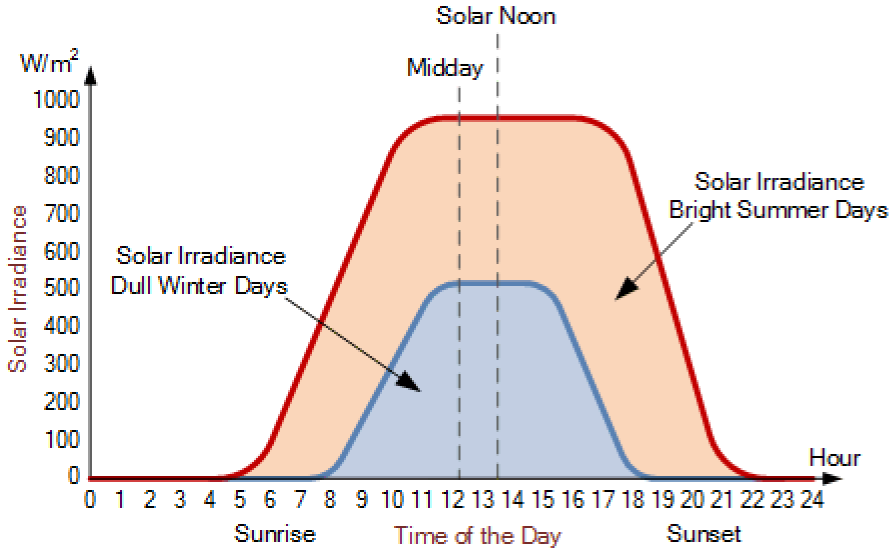

Figure1. 1: Graph of solar irradiation during the day

We can see from our daily example, that the solar irradiance available during the brighter sunnier and longer summer days is greater than that of the shorter, duller winter days as we would expect. So, the peak sun hours available during the summer is clearly longer than the winter period allowing a PV panel to operate at its peak rated output longer.

1.3. Types of Solar Irradiance

The radiation reaching the earth's surface can be represented in a number of different ways. A few ways of measurement are listed below. The study and measurement of solar irradiance helps us in predicting the amount of energy to be generated from solar power plants. And other applications such as in the heating and cooling loads of buildings, and climate modeling and weather forecasting.

There are several measured types of solar irradiance.

- Total Solar Irradiance (TSI): is a measure of the solar power over all wavelengths per unit area incident on the Earth's upper atmosphere. It is measured perpendicular to the incoming sunlight. The solar constant is a conventional measure of mean TSI at a distance of one astronomical unit (AU).

- Direct Normal Irradiance (DNI), or beam radiation, is measured at the surface of the Earth at a given location with a surface element perpendicular to the Sun. It excludes diffuse solar radiation (radiation that is scattered or reflected by atmospheric components). Direct irradiance is equal to the extra-terrestrial irradiance above the atmosphere minus the atmospheric losses due to absorption and scattering. Losses depend on time of day (length of light's path through the atmosphere depending on the solar elevation angle), cloud cover, moisture content and other contents. The irradiance above the atmosphere also varies with time of year (because the distance to the sun varies), although this effect is generally less significant compared to the effect of losses on DNI.

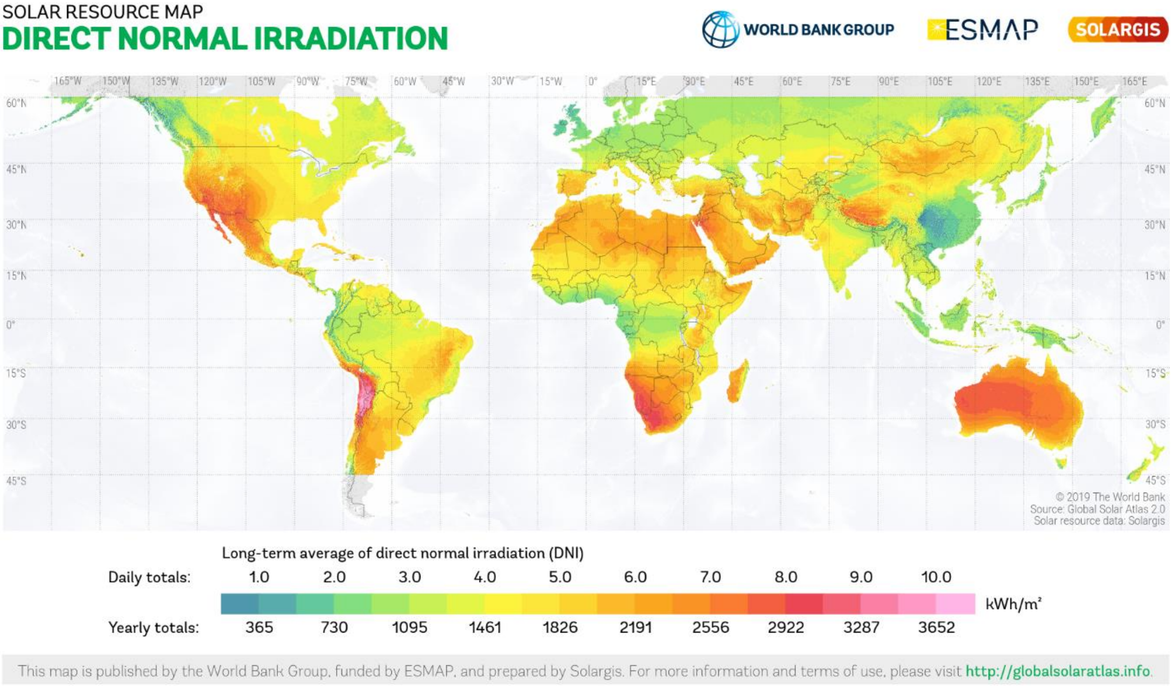

Figure1. 2 : Direct Normal Irradiation by country [69]

- Diffuse Horizontal Irradiance (DHI) is sometimes called Diffuse Sky Radiation is the radiation at the Earth's surface from light scattered by the atmosphere. It is measured on a horizontal surface with radiation coming from all points in the sky excluding circumsolar radiation (radiation coming from the sun disk). There would be almost no DHI in the absence of atmosphere. [69]

- Global Horizontal Irradiance (GHI) is the total irradiance from the sun on a horizontal surface on Earth. It is the sum of direct irradiance (after accounting for the solar zenith angle of the sun z) and diffuse horizontal irradiance:

$$GHI = DHI + DNI \times \cos(z)$$

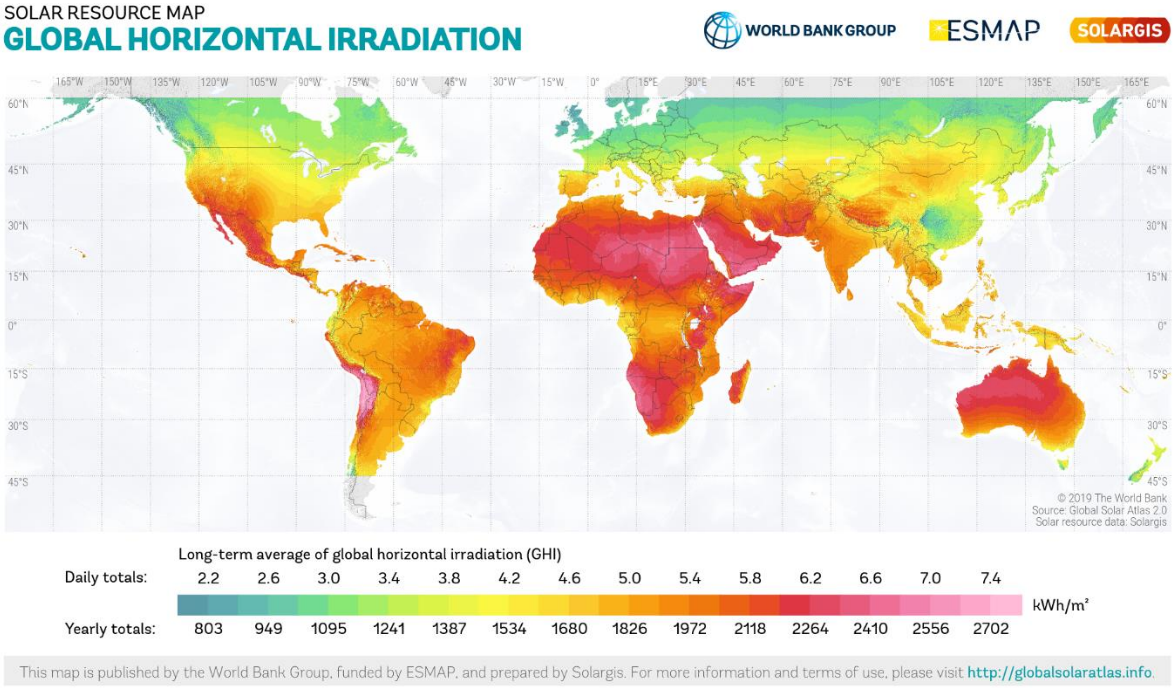

Figure1. 3: Global Horizontal Irradiation of countries [69]

- Global Tilted Irradiance (GTI) is the total radiation received on a surface with defined tilt and azimuth, fixed or sun-tracking. GTI can be measured or modelled from GHI, DNI, DHI. It is often a reference for photovoltaic power plants, while photovoltaic modules are mounted on the fixed or tracking constructions.

- Global Normal Irradiance (GNI) is the total irradiance from the sun at the surface of Earth at a given location with a surface element perpendicular to the Sun.

This values of particular interest in photovoltaic installations and includes Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF)

From the previous definitions and corresponding graphs, we can see that Africa is blessed with abundance solar energy which when properly harnessed can be a huge source of energy for our domestic needs. Therefore, the use of solar energy through solar powered plants and solar panels can help in tackling the energy issues faced by African countries.

Global Horizontal Irradiance (GHI) is the total amount of shortwave radiation received from above by a surface horizontal to the ground.

1.4. Photovoltaic Power Potential

This values of particular interest in photovoltaic installations and includes Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF). Also of interest is the photovoltaic power potential.

The photovoltaic potential represents the expected lifetime average electricity production (in kWh) produced per kilowatt of installed photovoltaic DC capacity rated at Standard Test Conditions (STC) for grid-connected PV systems without batteries.[68]

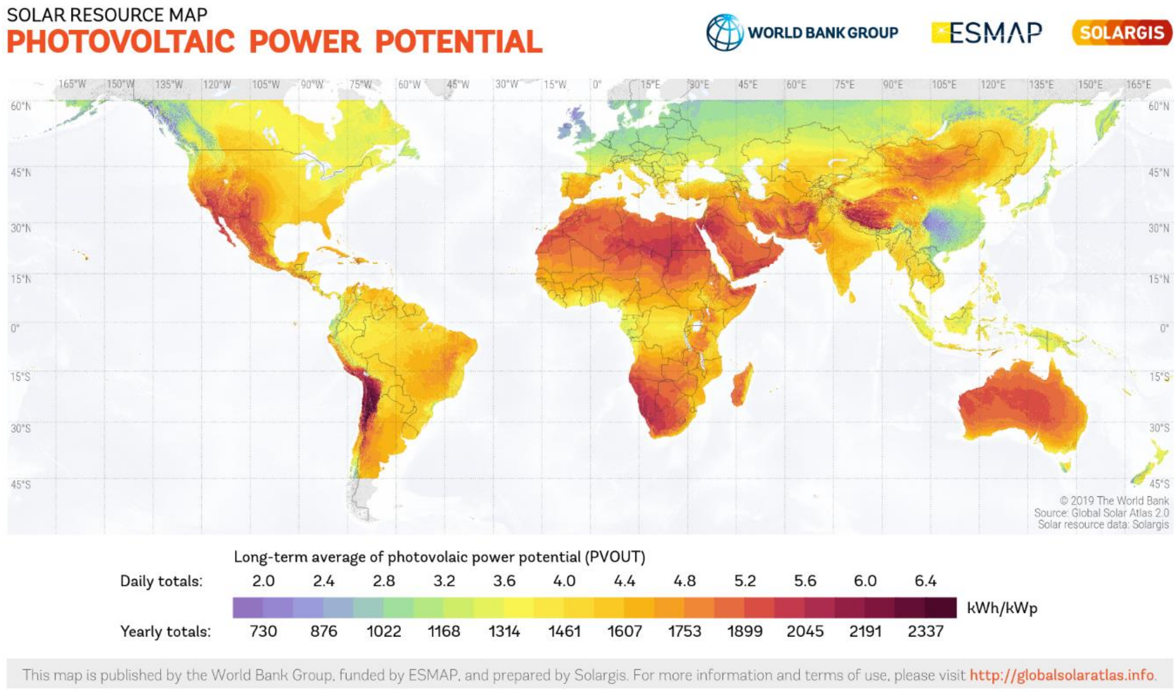

Figure1. 4 : Photovoltaic power potential by country [68]

1.5. Radiation, Irradiation, Irradiance and Insolation

The terms solar radiation, irradiation, irradiance and insolation are different and should not be used interchangeably.

- Radiation: The process of radiation can be defined as an emission of energy in the shape of electromagnetic waves. It happens to be in the form of subatomic particles that have a high ratio of energy and lead to a process known as ionization. A good example of that is what happens in the sun. Radiation refers to any energy that originates from a source and travels through some material or through space. Light, heat and sound are good examples. The other forms of electromagnetic radiation are radio waves, x-rays, and gamma rays. Therefore, Solar radiation is the energy we get from the sun, it is a generic term covering all forms of radiant energy falling on the surface of the earth and originating from the sun

- Irradiation: Solar irradiation is the quantity that measures the energy per unit area of incident solar radiation on a surface - the power received during a time (J/m^2 or Wh/m^2). Irradiation describes the radiation falling on to a surface - or simply, the exposure of a substance to radiation. Thus, it is the amount of solar radiation received by photovoltaic panels. Solar irradiation is equal to area under the curve between the solar Irradiance and the Time (hour, day, month, year). The symbol is H or sometimes I, the symbol "H" is used for insolation for a day while the symbol "I" is used for insolation for an hour (or other period if specified)

- Irradiance: Irradiance is the power of solar radiation per unit area received from the sun. In the international system of units, it is measured in (W/m2). It can be measured directly by using solarimeter or Pyranometer. In practice, the irradiance is usually measured by the average rate of accumulation of energy over one hour, for each hour of the day. The symbol is G.

- Insolation: Insolation refers to the quantity of solar radiation energy received on a surface (m^2) during an amount of time. In the photovoltaic industry it is commonly expressed as average irradiance in kilowatt per square meter (kW/ m^2) or - taking into account the time factor - kilowatt hours per year per kilowatt peak kWh/(kWp*year)

1.6. Solar Spectrum

The Sun emits radiation from X-rays to radio waves, but the irradiance of solar radiation peaks in the visible wavelengths. The solar spectrum consists of a continuum with thousands of dark absorption lines superposed. The lines are called the Fraunhofer lines, and the solar spectrum is sometimes called the Fraunhofer spectrum. These lines are produced primarily in the photosphere.

Solar radiation in the red to violet wavelengths blast a solar cell with enough energy to create electricity. But solar cells do not respond to all forms of light. Wavelengths in the infrared spectrum have too little of the energy needed to jostle electrons loose in the solar cell’s silicon, the effect that produces electric current. Ultraviolet wavelengths have too much energy. These wavelengths simply create heat, which can reduce a cell's efficiency. Solar cells require certain wavelengths in the light spectrum to generate useful amounts of electricity.

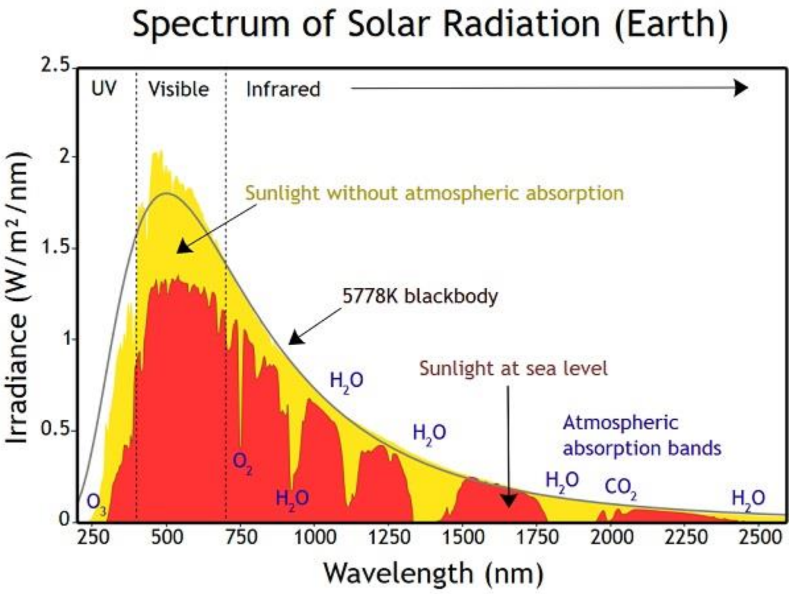

Figure1. 5: Solar spectrum

Solar cells generally work well with natural sunlight, as most uses for solar-powered devices are outdoors or in space. Because artificial sources of light such as incandescent and fluorescent bulbs mimic the Sun's spectrum, solar cells can also work indoors, powering small devices such as calculators and watches. Other artificial sources such as lasers and neon lamps have very restricted colour spectra; solar cells may not work as effectively with their light.

The energy in solar irradiation comes in the form of electromagnetic waves of a wide spectrum. Visible light starts at a wavelength of around 390 nanometres and ends at around 700 nanometres. The energy of the wavelength increases with the frequency and decreases with the size of the wavelength. Infrared with longer wavelengths have less energy than shorter ones such as visible light or UV.

The spectral energy distribution of solar light has a maximum in the visible portion. This is at around 1.5 eV and hence the semiconductor having band gap near 1.5 eV is preferred for solar cells. Since maxima in intensity occurs in the visible portion of sun light, only this portion is useful. The other portion of spectrum is not useful. It produces heat if absorbed or attempts are made to get it reflected. This is one of the reasons of low efficiency of solar cells as only 46 percent is visible portion. Thus, the efficiency of a solar panel depends on the solar irradiation spectrum and the absorption spectrum of the photovoltaic absorber. For an inorganic semiconductor absorber all the photons with energy above the energy gap are able to pump an electron from the valence band to the conduction band. So, with a low energy gap you have high current. But the higher the energy gap, the higher the theoretical photovoltaic. So, the power output is a trade-off of high current (small gap) and high voltage (large gap). For semiconductors, the optimum energy gap is in the range 1.1 to 1.7 eV

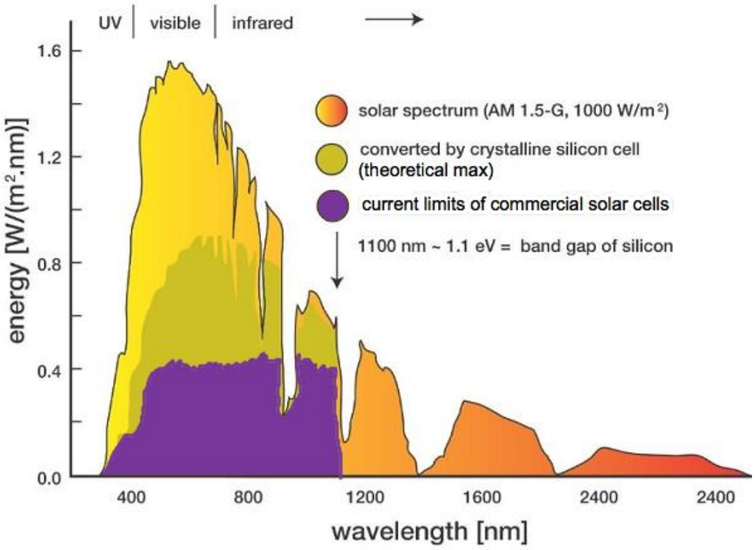

Figure1. 6: Solar spectrum absorbed by solar panels

Light having energy less than band gap of semiconductor does not produce electron hole pair and hence cannot be used for photovoltaic application. If the used semiconductor has band gap in the energy range of visible light, infrared portion will not be useful for photovoltaic application. For better efficiency, a wide range of wavelength needs to be absorbed. For this, multijunction cells are used. Multijunction solar cells (such as used in Concentrator photovoltaics also known as concentration photovoltaics CPV) try to use as much of the spectrum as possible. Wavelength-Selective Photovoltaic Systems (WSPVs) an also increase efficiency, WSPVs combine luminescent solar cell technology with conventional silicon-based PV, thereby increasing efficiency and lowering the cost of electricity generation. WSPVs absorb some of the blue and green wavelengths of the solar spectrum. They are ideal and mostly used for integrating electricity generation with agriculture in greenhouses.

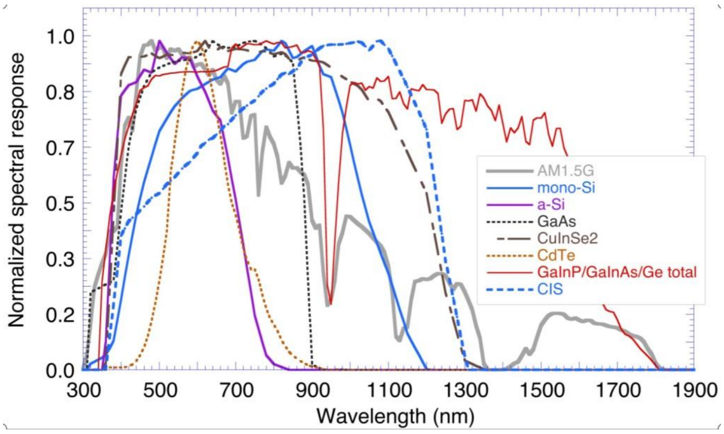

Figure1. 7: Solar technology absorption spectrum

In principle 3 types of silicon majorly used to make solar panels -mono crystalline, poly crystalline and CIS (copper (C), indium (I) and selenium (S)). Above in figure1.7 is a side-by-side comparison of how the types of silicon use light energy. If a solar panel is 20 % efficient at converting this light into electricity, then the majority of the other energy ends up as heat.

1.7. Solar Energy in Africa, Algeria, Zambia and Nigeria

1.7.1. Solar Energy in Africa

Endowed with a dense energy potential and even more so with the advent of the era of renewable energies, Africa is undoubtedly destined to eradicate the problem of electrification.

Notwithstanding all these assets available to the continent with regard to renewable and non-renewable energies, we note that the latter still suffers from problems of lack of energy and especially pollution due to the use of non-renewable energies (oil, gas,....) by large industrial firms.

However, we are witnessing the emergence of the use of solar energy, which requires research into the production and installation of photovoltaic equipment; what our memory will bear. We will focus on research on African countries in particular Algeria, Nigeria and Zambia

1.7.2. Solar potential in Algeria

Due to its geographical location, Algeria has one of the highest solar deposits in the world. The duration of sunshine on almost all of the national territory exceeds 2000 hours annually and can reach 3900 hours (high plateaus and Sahara). The energy received daily on a horizontal surface of 1m^2 is of the order of $5KWh$ over most of the national territory, i.e., nearly $1700KWh/m^2$/yr in the north and $2263Kwh/m^2$/yr in the south of the country.

In the Sahara, this potential can constitute an important factor of sustainable development if it is exploited in an economic way. The following table indicates the sunshine rate for each region of Algeria.[61]

Table1. 1: Sunshine rates of regions in Algeria

Regions	Coastal regions	Highlands	Sahara
Area	4%	10%	86%
Average sunshine duration (Hour/year)	2650	3000	3500
Average energy received (KWh/m^2/year)	1700	1900	2650

1.7.3. Solar Energy in Nigeria

Hungry for energy, millions of Nigerians put up with noisy, smoky petrol-fueled generators to power their lives. To bridge the gap between supply and demand, Nigerians are forced to generate power in small units from off-grid sources, usually fossil fuel-powered generators. Along with the financial cost of generators are health and environmental costs. Two out of three generator users in Nigeria complained of hearing impairment, according to data cited in a 2019 report by the Access to Energy Institute (A2EI), a non-profit research and development institute working to advance the use of solar energy in developing countries. [51]

Nigeria gets between five to seven hours of sunlight daily, depending on the region. A 2019 report by the director-general of the Energy Commission of Nigeria estimated that if one percent of Nigeria’s land area were to be covered with a solar technology of five percent efficiency, about 333,480 megawatts of electricity could be generated, which is “more than enough for the country”. [52]

Experts believe that solar power in Nigeria is currently underutilized. For example, Nigerians are likely to own a solar-powered torchlight, solar-powered fan and perhaps solar-powered refrigerator, but each comes with its own solar plate and energy generation unit, rather than plugging into a single solar generator capable of powering an entire house and every appliance.

1.7.4. Renewable energy investments in Nigeria

In December 2020, the Nigerian government launched the Solar Power Naija programme, an ambitious project targeted to provide solar electrification to 25 million Nigerians who were not previously connected to the grid. The programme plans to provide five million new off-grid or mini-grid connections and “incentivise the creation of 250,000 new jobs in the energy sector”, according to its website. However, since the programme’s inception, the Rural Electrification Agency — the agency in charge of the programme — has so far deployed 100,000 solar home systems. We only hope that with these initiatives, more plans Nigeria can be one of Africa’s leading solar energy producers, and even further, more join the world scale. [63]

1.8. Conclusion

Solar energy is the energy received from the sun in the form of light, heat and electromagnetic radiation. For application in photovoltaic systems, the radiation and light are what is used to generate electricity by solar panels. The photovoltaic potential of the sun in Algeria, Nigeria, Zambia and Africa at large is enormous and should be harnessed properly to meet our ever-increasing energy needs.

The terms solar radiation, irradiation, irradiance and insolation can be confusing due to linguistic closeness. Great care should me made when being used in order to be used correctly. Solar radiation is all the radiant energy emitted by the sun while solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation measured in space or at the Earth's surface. And lasty, insolation is the total solar radiation that reaches the earth's surface. It is measured by the amount of solar energy received per square centimetre per minute.

Mostly visible light from the sun’s solar spectrum is absorbed by solar panels for their generation of electricity. Multijunction cell using different dopers which have different electron band gap helps to improve their efficiency.

CHAPTER 2

Photovoltaic Systems

2.1. Introduction to photovoltaic systems

Solar cells, also called photovoltaic cells, convert sunlight directly into electricity using photovoltaic effect. The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons (like energy accumulations), or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons hit a PV cell, they may be reflected or absorbed. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the cell (usually silicon atoms). The electron is able to escape from its normal position associated in the atom to become part of the current in an electrical circuit.[1]

Solar photovoltaic modules are where the electricity gets generated, a photovoltaic panel alone does not constitute a photovoltaic PV system but are only one of the many parts in a complete photovoltaic (PV) system. In order for the generated electricity to be useful in a home or business, a number of other technologies must be in place. PV systems can be very simple, consisting of just a PV module and load, as in the direct powering of a water pump motor, which only needs to operate when the sun shines. However, when for example a whole house should be powered, the system must be operational day and night. It also may have to feed both AC and DC loads, have reserve power and may even include a back-up generator. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid. PV systems are adapted to meet particular requirements by varying the type and quantity of the basic elements.

2.2. Brief history and development of solar panel

2.2.1. Early history

In 1839, French scientist Edmond Becquerel discovered the photovoltaic effect at the young age of 19. He realized when electrons were in an excited state in a conduction band, they could move freely through a material, thus creating a current. But this wasn’t widely recognized until Einstein wrote a paper about the power of solar for which he eventually received the Nobel prize in 1922. The first solar panel was invented by Charles Fritts in 1883 where he coated a thin layer of selenium with an extremely thin layer of gold. The resulting cells had a conversion electrical efficiency of only about 1%. This invention led to the launching of a movement for producing solar energy.[65]

The solar era began in 1950 when Bell Laboratory scientists focused on photovoltaic developments and began utilizing silicon to produce solar cells. This breakthrough is credited to Daryl Chapin, Calvin Fuller, and Gerald Pearson which produced an efficiency of 4% only. This breakthrough led the US government to pour more money into solar cell technology. In the 1960s and 1970's the production of solar panels was made possible but the downside was it was too expensive for mainstream consumers but scientists continued to develop solar energy technology to reduce the cost. With the rise of semiconductors in 1941, Russel S Ohl described a process of forming silicon ingots that led to the first P-N junction cell. Ohl cut a section from the ingot including the top, barrier, and bottom portions, and attached electrodes to the top and bottom portions, yielding the first silicon solar cell.

2.2.2. Solar panel in the 2000s

The evolution of the solar PV industry so far has been remarkable, with several milestones achieved in recent years in terms of installations (including off-grid), cost reductions and technological advancements, as well as establishment of key solar energy associations. Most modern solar panel have efficiencies over 20%.

2.2.3. Future of solar panels

Rising concerns about climate change, the health effects of air pollution, energy security and energy access, along with volatile oil prices in recent decades, have led to the need to produce and use alternative, low-carbon technology options such as renewables. With the world's accelerating shift from climate-damaging fossil fuels towards clean, renewable forms of energy. The steady rise of solar photovoltaic power generation forms a vital part of this global energy transformation.

Considering ample resource availability, significant market potential and cost competitiveness, solar PV is expected to continue driving overall renewables growth in several regions over the next decade. Progress in research and development is continuously being made in both existing and emerging technologies in PV technologies, efficiency, materials and module manufacturing.

With the Net Zero Emissions by 2050 agreed to by countries of the world and decarbonization path compatible with the Paris Agreement, solar energy will be more used in the years to come.

2.3. Semi-conductors and solar cells

2.3.1. Semi-conductors

Semiconductors materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a conductor and an insulator. They are not good conductors nor good insulators (hence their name semi-conductors). They have very few free electrons because their atoms are closely grouped together in a crystalline pattern called a crystal lattice but electrons are still able to flow, but only under special conditions such as when dopants are added.

The process of deliberately introducing other elements into a crystal is called doping. The element introduced by doping is called a dopant. By carefully controlling the doping process and the dopants that are used, silicon crystals can transform into one of two distinct types of conductors:

- **N-type semiconductor:** Created when the dopant is an element that has five electrons in its valence layer. Phosphorus is commonly used for this purpose. Because the phosphorus atom has five electrons in its valence shell, but only four of them are bonded to adjacent atoms, the fifth valence electron is left hanging out with nothing to bond to. The extra valence electrons in the phosphorous atoms start to behave like the single valence electrons in a regular conductor such as copper. They are free to move about. Because this type of semiconductor has extra electrons, it's called an N-type semiconductor.
- **P-type semiconductor:** Happens when the dopant (such as boron) has only three electrons in the valence shell. When a small amount is incorporated into the crystal, the atom is able to bond with four silicon atoms, but since it has only three electrons to offer, a hole is created. The hole behaves like a positive charge, so semiconductors doped in this way are called P-type semiconductors. Like a positive charge, holes attract electrons. But when an electron moves into a hole, the electron leaves a new hole at its previous location. Thus, in a P-type semiconductor, holes are constantly moving around within the crystal as electrons constantly try to fill them up.

When voltage is applied to either an N-type or a P-type semiconductor, current flows, for the same reason that it flows in a regular conductor: The negative side of the voltage pushes electrons, and the positive side pulls them. The result is that the random electron and hole movement that's always present in a semiconductor becomes organized in one direction, creating measurable electric current.

2.3.2. Solar cell

When light strikes the semiconductor of a photovoltaic cell energy is absorbed. Electrons are promoted to the conduction band and holes are formed in the valence band. These charge carriers could travel through an external circuit and do useful work or they could simply recombine and give off their energy as heat.[4]

A photovoltaic cell must have two types of semiconductors in layers, the n-type semiconductor and the p-type semiconductor. When put together in a pn junction, an electric field forms at the junction that biases the flow of electrons and holes to opposite directions. This reduces electron-hole recombination.

2.4. PV Hierarchy

A cell is defined as the semiconductor device that converts sunlight into electricity. A PV module refers to a number of cells connected in series and in a PV array, modules are connected in series and in parallel

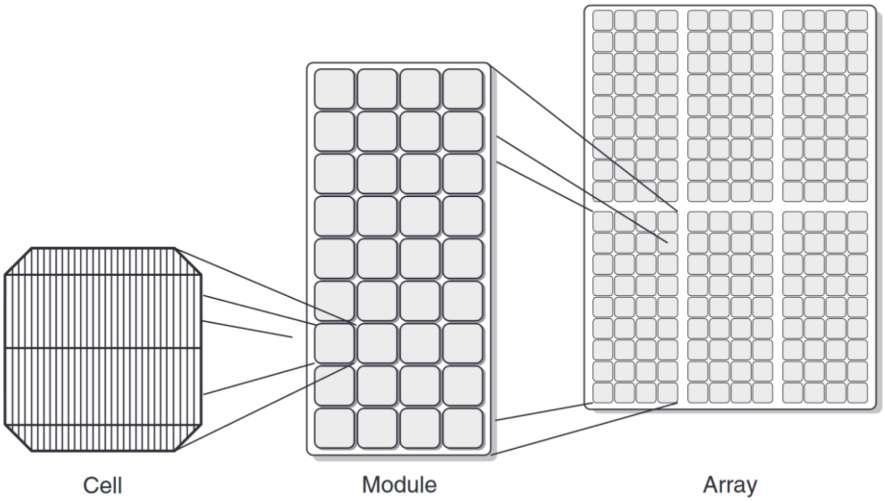

Figure 2. 1 : A PV cell, module and array

2.4.1. PV Cell

PVs generate electric power when illuminated by sunlight or artificial light. To illustrate the operation of a PV cell the p-n homojunction cell is used. PV cells contain a junction between two different materials across which there is a built-in electric field. The absorption of photons of energy greater than the bandgap energy of the semiconductor promotes electrons from the valence band to the conduction band, creating hole-electron pairs throughout the illuminated part of the semiconductor. These electron and hole pairs will flow in opposite directions across the junction thereby creating DC power.

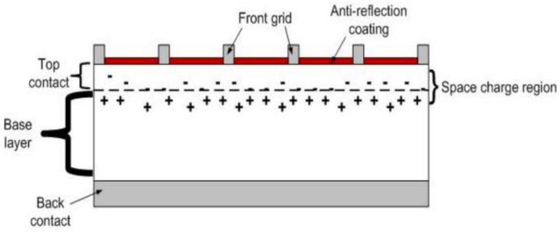

Figure 2. 2: Structure of a PV Cell

The cross-section of a PV cell is shown in Figure 2.2. The most common material used in PV cell manufacture is mono-crystalline or poly-crystalline silicon. Each cell is typically made of square or rectangular wafers of dimensions measuring about 10cm × 10cm × 0.3mm. In the dark the PV cell’s behaviour is similar to that of a diode and the well-known Shockley-Read equation can be used to model its behaviour i.e. [4]

$$i = I_s(e^{\frac{qV}{nkT}} - 1) \qquad \text{Eq 2. 1}$$

2.4.2. Module

For the majority of applications multiple solar cells need to be connected in series or in parallel to produce enough voltage and power. Individual cells are usually connected into a series string of cells (typically 36 or 72) to achieve the desired output voltage. The complete assembly is usually referred to as a module and manufacturers basically sell modules to customers. The modules serve another function of protecting individual cells from water, dust etc. as the solar cells are placed into an encapsulation of single or double flat glasses.[2]

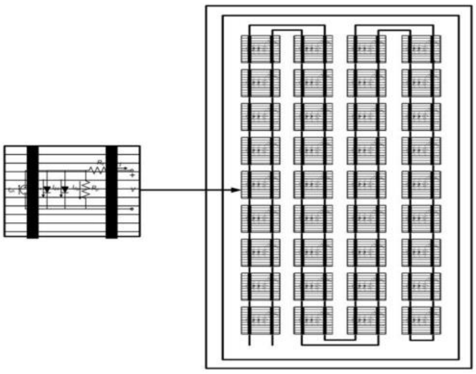

Figure 2. 3: Structure of a PV Module

Within a module the different cells are connected electrically in series or in parallel although most modules have a series connection. Figure 2.3 shows a typical connection of how 36 cells are connected in series. In a series connection the same current flows through all the cells and the voltage at the module terminals is the sum of the individual voltages of each cell. It is therefore, very critical for the cells to be well matched in the series string so that all cells operate at the maximum power points. When modules are connected in parallel the current will be the sum of the individual cell currents and the output voltage will equal that of a single cell.

2.4.3. Array

An array is a structure that consists of a number of PV modules, mounted on the same plane with electrical connections to provide enough electrical power for a given application. Arrays range in power capacity from a few hundred watts to hundreds of kilowatts. The connection of modules in an array is similar to the connection of cells in a single module. To increase the voltage, modules are connected in series and to increase the current they are connected in parallel. Matching is again very important for the overall performance of the array. The structure of an array is shown in figure 2.4, which has 4 parallel connections of 4 module strings connected in series.

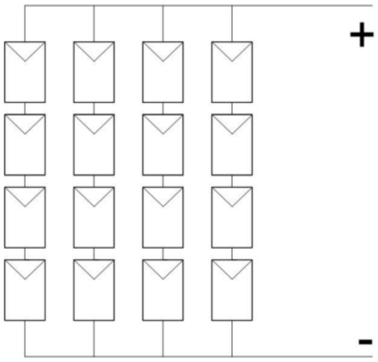

Figure 2. 4: Structure of a PV array

The voltages for n modules in series is given as:

$$V_{series} = \sum_{j=1}^{n} V_j = V_1 + V_2 + \cdots + V_n \quad for I > 0 \qquad Eq\ 2.\ 2$$

$$V_{seriesOC} = \sum_{j=1}^{n} V_j = V_{OC1} + V_{OC2} + \cdots + V_{OCn} \quad for I = 0 \qquad Eq\ 2.\ 3$$

The current and voltage for m modules in parallel is given by:

$$I_{parallel} = \sum_{j=1}^{m} I_j = I_1 + I_2 + \cdots + I_m \qquad \text{Eq 2. 4}$$

$$V_{parallel} = V_1 = V_2 = \cdots = V_m \qquad \text{Eq 2. 5}$$

For an array to perform well all the modules must not be shaded otherwise it will act as a load resulting in heat that may cause damage. Bypass diodes are usually used to avoid damage although they result in further increase in cost. Integration of bypass diodes in some large modules during manufacturing is not uncommon and reduces the extra wiring required. It must be pointed out though that it becomes very difficult to replace the diode if it fails.

2.5. Functioning principle of a PV system

The word “photovoltaic” consists of two words: photo, a Greek word for light, and voltaic, which defines the measurement value by which the activity of the electric field is expressed, i.e., the difference of potentials. Photovoltaic systems use cells to convert sunlight into electricity. Converting solar energy into electricity in a photovoltaic installation is the most known way of using solar energy.[66] []

The light has a dual character according to quantum physics. Light is a particle and it is a wave. The particles of light are called photons. Photons are massless particles, moving at light speed. The energy of the photon depends on its wavelength and the frequency, and we can calculate it by the Einstein's law, which is:

$$E = hv \qquad \text{Eq 2. 6}$$

Where:

E - photon energy
h - Planck's constant = 6.626×10^{-34} Js
v- photon frequency

In metals and in the matter generally, electrons can exist as valence or as free. Valence electrons are associated with the atom, while the free electrons can move freely. In order for the valence electron to become free, he must get the energy that is greater than or equal to the energy of binding. Binding energy is the energy by which an electron is bound to an atom in one of the atomic bonds. In the case of photoelectric effect, the electron acquires the required energy by the collision with a photon. Part of the photon energy is consumed for the electron getting free from the influence of the atom which it is attached to, and the remaining energy is converted into kinetic energy of a now free electron. Free electrons obtained by the photoelectric effect are also called photoelectrons. The energy required to release a valence electron from the impact of an atom is called a “work out” Wi, and it depends on the type of material in which the photoelectric effect has occurred. The equation that describes this process is as follows:

$$hv = W_i + E_{kin} \qquad \text{Eq 2. 7}$$

hv – photon energy
W_i – work out
E_{kin} – kinetic energy of emitted electron

The previous equation shows that the electron will be released if the photon energy is less than the work output. The photoelectric conversion in the PV junction. PV junction (diode) is a boundary between two differently doped semiconductor layers; one is a P-type layer (excess holes), and the second one is an N-type (excess electrons). At the boundary between the P and the N area, there is a spontaneous electric field, which affects the generated electrons and holes and determines the direction of the current.

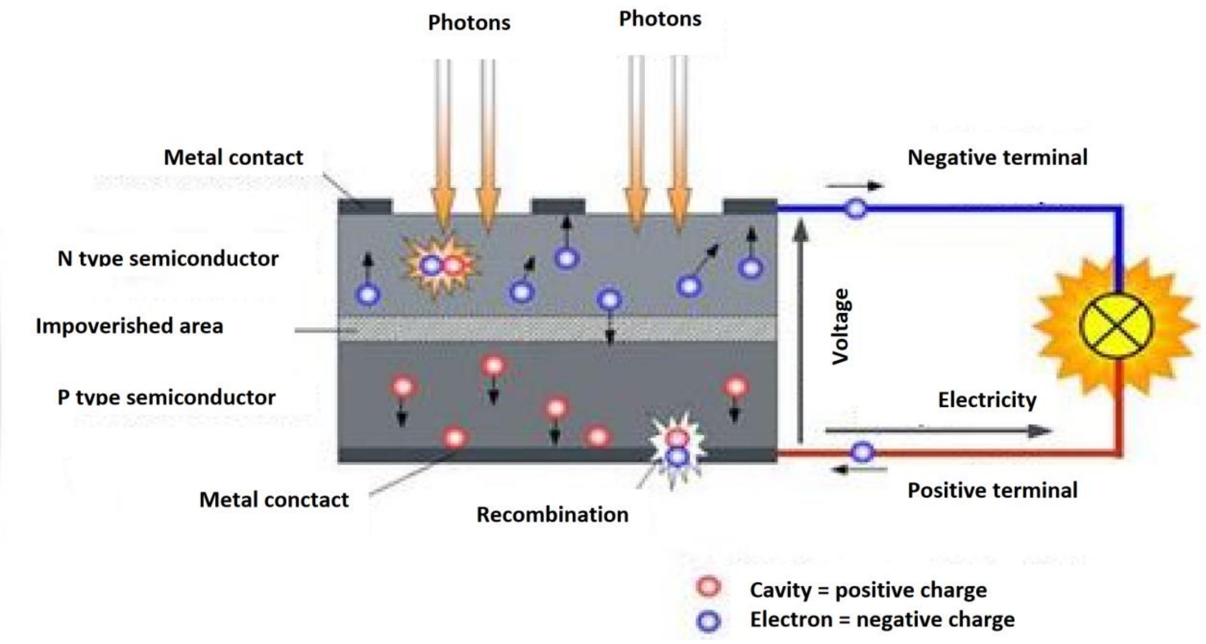

Figure 2. 5: Functioning principle of a photovoltaic cell

2.6. Usefulness and Efficiency

2.6.1. Usefulness:

The usefulness of a photovoltaic solar cell is defined as the ratio of electric power provided by the PV solar cells and the solar radiation power. Mathematically, it can be presented in the following relation:

$$\eta = \frac{P_{el}}{P_{sol}} = \frac{U\,.\,I}{E\,.\,A} \qquad \text{Eq 2. 8}$$

Where: P_{el} = Electrical Output power
P_{sol} – Radiation Power (Sun)
I – Effective value of output current
U – Effective value of output voltage
E – Specific radiation power (W/m^2)
A – Area

The usefulness of PV solar cells ranges from a few percent to forty percent. The remaining energy that is not converted into electrical energy is mainly converted into heat energy and thus warms the cell. Generally, the increase in solar cell temperature reduces the usefulness of PV cells.

2.6.2. Efficiency:

Energy conversion efficiency of a solar photovoltaic cell (η "ETA") is the percentage of energy from the incident light that actually ends up as electricity. This is calculated at the point of maximum power, Pm, divided by the input light irradiation (E, in W/m^2), all under standard test conditions (STC) and the surface of photovoltaic solar cells (AC in m^2).

$$\eta = \frac{P_m}{A_c \times E} \qquad \text{Eq 2. 9}$$

STC - standard test conditions, according to which the reference solar radiation is 1000 W/m 2, spectral distribution is 1.5 and cell temperature 25℃.

2.7. TYPES OF PHOTOVOLTAIC SYSTEMS

Photovoltaic-based systems are generally classified according to their functional and operational requirements, their component configuration, and how the equipment is connected to the other power sources and electrical loads (appliances).[2]

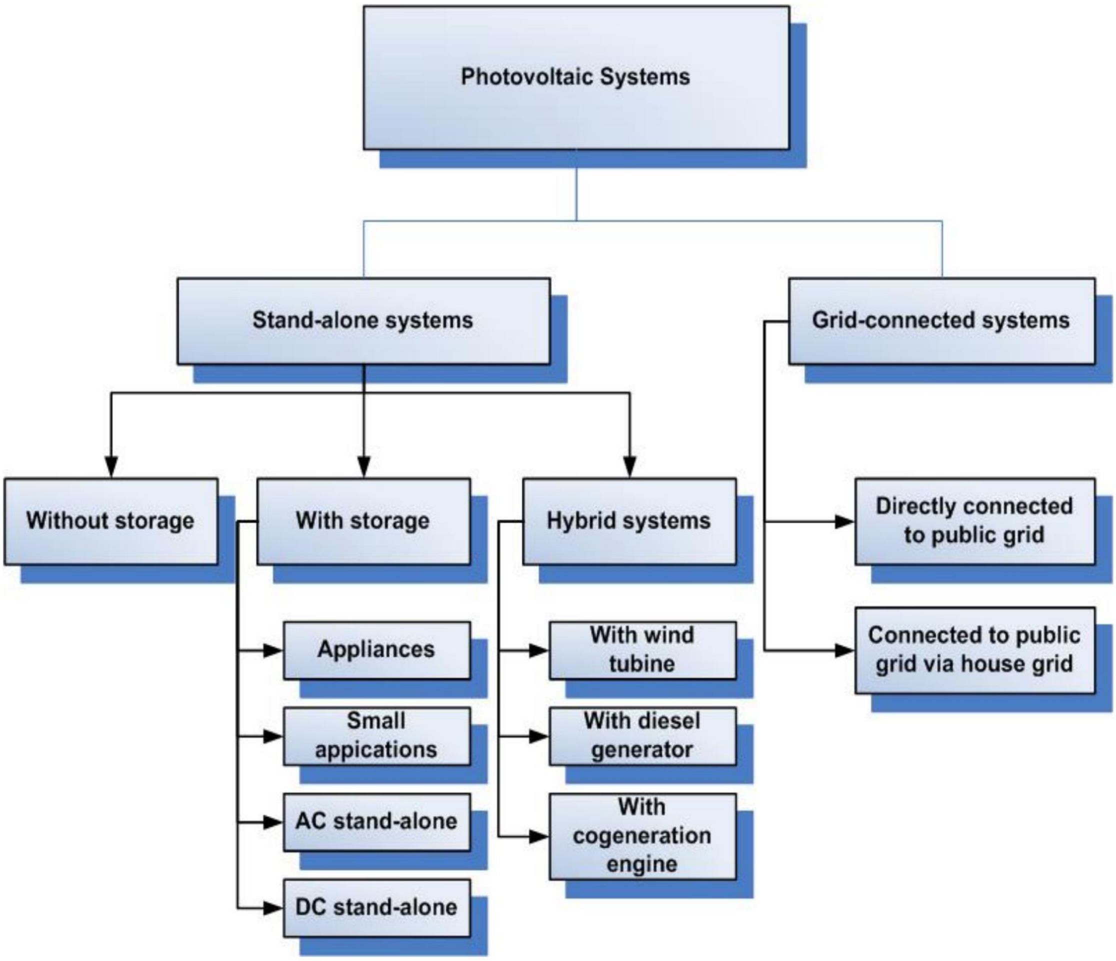

Figure 2. 6: Types of PV system

2.7.1. Grid Connected Systems

A grid connected PV system is one where the photovoltaic panels or array are connected to the utility grid through a power inverter unit allowing them to operate in parallel with the electric utility grid.

Grid Connected PV Systems have solar panels that provide some or even most of their power needs during the day time, while still being connected to the local electrical grid network during the night time, especially during the long hot summer months. Solar powered PV systems can sometimes produce more electricity than is actually needed or consumed. This extra or surplus electricity is either stored in batteries or as in most grid connected PV systems, fed directly back into the electrical grid network.

In other words, homes and buildings that use a grid connected PV system can use a portion or all of their energy needs with solar energy, and still use power from the normal electrical mains grid during the night or on cloudy dull and rainy days, giving the best of both worlds. Then in grid connected PV systems, electricity flows back-and-forth to and from the mains grid according to sunlight conditions and the actual electrical demand at that time.

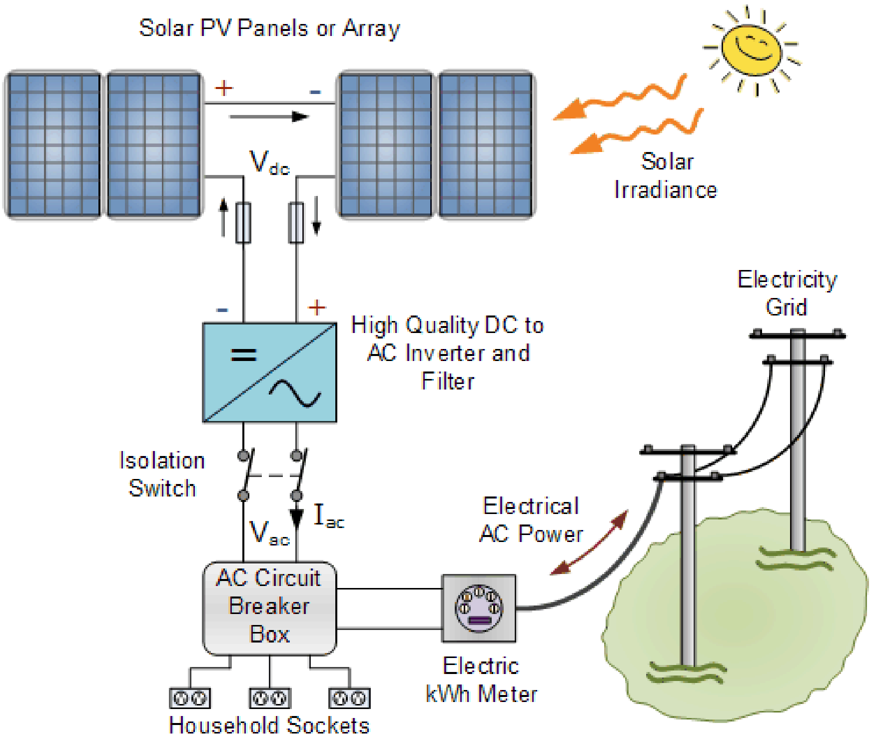

Figure 2. 7: Grid-connected system

A grid connected system is connected to a larger independent grid (typically the public electricity grid) and feeds energy directly into the grid. This energy may be shared by a residential or commercial building before or after the revenue measurement point, depending on whether the credited energy production is calculated independently of the customer's energy consumption (feed-in tariff) or only on the difference of energy (net metering). These systems vary in size from residential (2–10 kWp) to solar power stations (up to 10s of MWp). This is a form of decentralized electricity generation. Feeding electricity into the grid requires the transformation of DC into AC by a special, synchronising grid-tie inverter. In kilowatt-sized installations the DC side system voltage is as high as permitted (typically 1000 V except US residential 600 V) to limit ohmic losses. Most modules (60 or 72 crystalline silicon cells) generate 160 W to 300 W at 36 volts. It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. An individual set of modules connected in series is known as a 'string'

2.7.2. Off Grid or Standalone

A stand-alone or off-grid system is not connected to the electrical grid. Standalone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft.

If the load is to be supplied independently of solar insolation, the generated power is stored and buffered with a battery. In non-portable applications where weight is not an issue, such as in buildings, lead acid batteries are most commonly used for their low cost and tolerance for abuse.

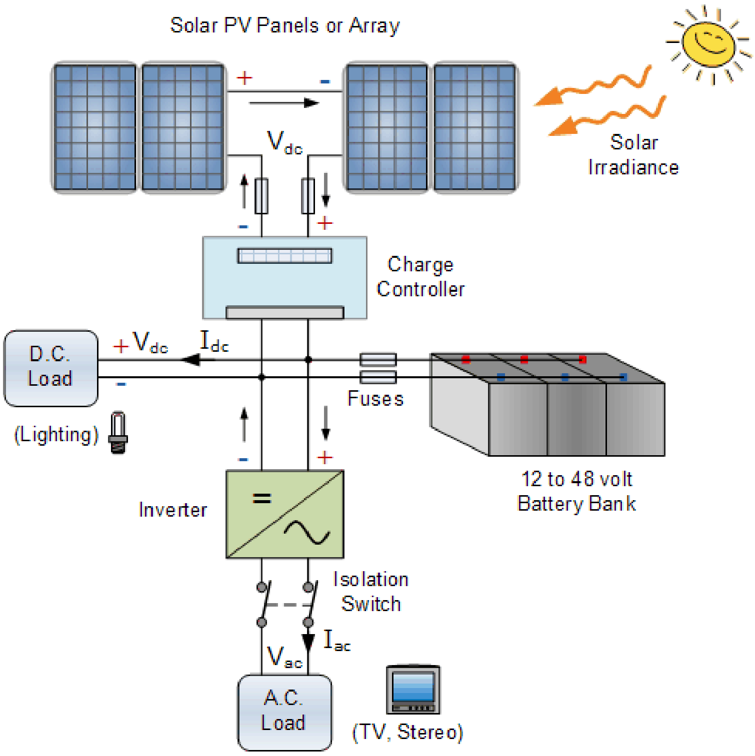

Figure 2. 8: Off-grid system

A charge controller may be incorporated in the system to avoid battery damage by excessive charging or discharging. It may also help to optimize production from the solar array using a maximum power point tracking technique (MPPT). However, in simple PV systems where the PV module voltage is matched to the battery voltage, the use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from the PV module. In small devices (e.g., calculators, parking meters) only direct current (DC) is consumed. In larger systems (e.g., buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used.

In agricultural settings, the array may be used to directly power DC pumps, without the need for an inverter. In remote settings such as mountainous areas, islands, or other places where a power grid is unavailable, solar arrays can be used as the sole source of electricity, usually by charging a storage battery. Stand-alone systems closely relate to microgeneration and distributed generation. Examples of standalone systems include

- Pico PV systems
- Solar street lights

- Telecommunication and signalling
- Solar vehicles
- Solar pumps
- Spacecraft

2.7.3. Hybrid Systems

A hybrid system combines PV with other forms of generation, usually a diesel generator. Biogas is also used. The other form of generation may be a type able to modulate power output as a function of demand. However more than one renewable form of energy may be used e.g., wind. The photovoltaic power generation serves to reduce the consumption of non-renewable fuel. A hybrid system ensures that energy demands are met while fully utilizing the PV supply. Usual forms of hybrid system include but not limited to:

- PVT system (hybrid PV/T), also known as photovoltaic thermal hybrid solar collectors convert solar radiation into thermal and electrical energy. Such a system combines a solar (PV) module with a solar thermal collector in a complementary way.
- CPVT system. A concentrated photovoltaic thermal hybrid (CPVT) system is similar to a PVT system. It uses concentrated photovoltaics (CPV) instead of conventional PV technology, and combines it with a solar thermal collector.
- CPV/CSP system. A novel solar CPV/CSP hybrid system has been proposed, combining concentrator photovoltaics with the non-PV technology of concentrated solar power (CSP), or also known as concentrated solar thermal.
- PV diesel system. It combines a photovoltaic system with a diesel generator. Combinations with other renewables are possible and include wind turbines

2.8. PHOTOVOLTAIC SYSTEM COMPONENTS

The photovoltaic system consists of a large number of parts that allow it to function efficiently and correctly. In order to operate and generate electricity, a number of features must be set in place. Therefore, a solar PV system consists of the following.[9]

2.8.1. Solar Array

A solar photovoltaic array consists of a number of solar PV panels that are electrically connected. The solar PV array generates DC electricity from sunlight.

Thanks to the flexibility of modular photovoltaic arrays, PV systems offer many different designs and a wide variety of electrical needs, regardless of how large or small the installation surface is.

It is important to keep in mind that photovoltaic systems must be installed on stable mounting structures that can support the array and withstand weather conditions like wind, rain, and corrosion for the next few decades

2.8.2. Mounting

Modules are assembled into arrays on some kind of mounting system, which may be classified as ground mount, roof mount or pole mount. For solar parks a large rack is mounted on the ground, and the modules mounted on the rack. For buildings, many different racks have been devised for pitched roofs. For flat roofs, racks, bins and building integrated solutions are used. Solar panel racks mounted on top of poles can be stationary or moving, see Trackers below. Side-of-pole mounts are suitable for situations where a pole has something else mounted at its top, such as a light fixture or an antenna. Pole mounting raises what would otherwise be a ground mounted array above weed shadows and livestock, and may satisfy electrical code requirements regarding inaccessibility of exposed wiring. Pole mounted panels are open to more cooling air on their underside, which increases performance. A multiplicity of pole top racks can be formed into a parking carport or other shade structure. A rack which does not follow the sun from left to right may allow seasonal adjustment up or down

- Pole mount
- Ground mount
- Roof mount:
    - Rack mount:
    - Direct mount:
    - Integrated mount
- Tracking Mounts:
    - Single axis
    - Dual axis

2.8.3. Cabling

Due to their outdoor usage, solar cables are designed to be resistant against UV radiation and extremely high temperature fluctuations and are generally unaffected by the weather. Standards specifying the usage of electrical wiring in PV systems include the IEC 60364 by the International Electrotechnical Commission

2.8.4. Tracker

A solar tracking system tilts a solar panel throughout the day. Depending on the type of tracking system, the panel is either aimed directly at the Sun or the brightest area of a partly clouded sky. Trackers greatly enhance early morning and late afternoon performance, increasing the total amount of power produced by a system by about 20–25% for a single axis tracker and about 30% or more for a dual axis tracker, depending on latitude.

Trackers are effective in regions that receive a large portion of sunlight directly. In diffuse light (i.e., under cloud or fog), tracking has little or no value. Because most concentrated photovoltaics systems are very sensitive to the sunlight's angle, tracking systems allow them to produce useful power for more than a brief period each day. Tracking systems improve performance for two main reasons. First, when a solar panel is perpendicular to the sunlight, it receives more light on its surface than if it were angled. Second, direct light is used more efficiently than angled light. Special Anti-reflective coatings can improve solar panel efficiency for direct and angled light, somewhat reducing the benefit of tracking.

Trackers and sensors to optimise the performance are often seen as optional, but they can increase viable output by up to 45%. Arrays that approach or exceed one megawatt often use solar trackers

2.8.5. Inverter

There are two types of power inverters that are used in all photovoltaic systems. Grid-direct systems use a grid-tied inverter that can interact with the utility grid. This type of inverter is different from the inverters in off-grid or grid-hybrid systems because it does not run off of batteries. The off-grid and grid-hybrid systems use battery-powered inverters. Both types of inverters perform the same essential function in these systems: they convert DC power to AC power.

In the grid-hybrid and off-grid systems, solar energy that is not used immediately is stored in a battery system. The DC power that is stored in a battery can be converted to AC power using a power inverter. A power inverter is a device that converts DC power into AC power. The battery array in a photovoltaic system can be used to run a power inverter, power electronics or other BOS components. The components can be directly powered using DC power or indirectly using AC power. The DC-to-AC converter is required because almost all home electronics require 220V AC power.

2.8.6. Battery

Batteries are used to store the energy generated by a solar array. Home-based solar arrays generate their largest power output in the middle of the day when most people are away from their homes. If the energy is not used immediately, it can be stored in a battery array. In a grid-hybrid system, any extra electricity generated after the batteries are charged can be sent back to the power grid.

Batteries supply DC power for a certain amount of time. The lifetime of a battery will depend on the current that the battery supplies and the maximum charge the battery can hold. The maximum charge of a battery is typically listed on the battery in units of milliamp-hours (mAh). This unit expresses the current the battery can supply and the amount of time it can supply the current.

2.8.7. Charge Controllers

Charge controllers take some of the electricity from the DC current generated by a solar array and use it to charge a battery or a group of batteries. The charge controller regulates the voltage and current generated by a solar array so that it can properly charge the battery or bank of batteries. The power generated by solar panels varies with light (photon) exposure. If a charge controller was not present in the photovoltaic system, the batteries could be overcharged and may be damaged.

The nominal and maximum voltage and current specifications on the charge controller will determine the number of charge controllers required to gather energy from the solar array. If a solar array generates a maximum current of 16 A, but a charge controller only accepts a maximum current of 10 A, the solar array can be divided into two parts. Each half of the array can generate a maximum 8 A of current, and each half of the array can be connected to the 10 A charge controller. The other option would be to use a charge controller with a larger current rating. Most charge controllers have very high current ratings (at least 40 amps), and the need for more than one charge controller only becomes an issue with very large solar arrays.

Charge controllers can be divided into two types: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). The PWN is a standard type and is suitable for smaller photovoltaic systems and battery banks, as they vary between 4 and 60 amperes.

On the other hand, the MPPT charge controllers are more suitable for photovoltaic systems with a high voltage of — in most cases — up to 160 volts DC.

Since not every photovoltaic system has a solar battery bank, it is not always necessary to include a charge controller into your system. In other words, you only need a charge controller if you have a battery bank

2.8.8. Safety and grounding equipment

Safety and grounding equipment is required for safety and fire prevention purposes. Automatic and manual safety disconnects protect the wiring and components of a photovoltaic system from power surges and other equipment malfunctions. They also ensure that your system can be shut down safely for maintenance and repair. In the case of grid-connected systems, safety disconnects also allow a photovoltaic system to be disconnected from the grid; this is important for the safety of people working on the grid transmission and distribution systems.

Grounding equipment provides a low-resistance path from your system to the ground to protect a photovoltaic system against current surges from lightning strikes or other equipment malfunctions. Users will need to create a grounded connection that is common to all of the balance-of-system equipment. This includes any exposed metal (such as the chassis of equipment boxes) that could potentially be touched by the customer or a technician.

2.9. PV TECHNOLOGIES

PV technologies are also known as solar panels. Below, we enumerated the different types of PV technologies available.[11]

Figure 2. 9: Types of PV technologies

2.9.1. Mono Crystalline

Mono-crystalline silicon cells have in the past dominated the PV market but have now been overtaken by poly-crystalline silicon. The popularity of mono-crystalline silicon was due to the good stability and desirable electronic, physical and chemical properties of silicon. Moreover, silicon was already successful in microelectronics and the enormous industry thus created would benefit the smaller PV industry with regards to economy of scale.

Figure 2. 10: Mono crystalline solar panel

2.9.2. Polycrystalline

This is the currently most dominant material and has surpassed the mono-crystalline because it is cheaper. The cost of silicon is a significant portion of the cost of the solar cell. The manufacturing processes of poly-crystalline silicon reduces the cost of silicon by avoiding pulling in the manufacturing process and it results in a block with a large crystal grain structure. This results in cheaper cells with a somewhat lower efficiency. The assembly of multi-crystal wafers is easier and therefore offsets the low efficiency disadvantage.

Figure 2. 11: Poly crystalline solar panel

2.9.3. Thin-film technology

In the thin-film technology the modules are manufactured by piling extremely thin layers of photosensitive materials on a cheap substrate such as glass, stainless steel or plastic. The process of generating modules in thin-film technology has resulted in reduced production costs compared to crystalline silicon technology, which is somewhat more intense. Today's price advantage in the production of a thin-film is balanced with the crystalline silicon due to lower efficiency of the thin-film, which ranges from 5% to 13%. The share of thin-film technology on the market is 15% and constantly increasing, it is also expected an increase in years to come and thus reduce the adverse market ratio in relation to the photovoltaic module of crystalline silicon. Lifespan is around 15-20 years.

Unlike crystalline panels that use silicon, thin-film solar panels are made from different materials. These are:

- Cadmium telluride (CdTe)
- Amorphous silicon (a-Si)
- Copper indium gallium selenide (CIGS)

2.1.1. Cadmium telluride (CdTe)

CdTe has the same low-cost advantage as polycrystalline cells while possessing the lowest carbon footprint, water requirement, and energy payback time of all solar panels types. However, the toxic nature of cadmium makes recycling more expensive than other materials.

2.1.2. Amorphous silicon (a-Si)

Amorphous silicon panels (A-Si) derive their name from their shapeless nature. Unlike mono-and polycrystalline solar cells, the silicon is not structured on the molecular level.

On average, an a-Si cell requires only a fraction of the silicon needed to produce typical silicon cells. This allows them to have the lowest production cost, at the expense of efficiency. This is why a-Si panels are suited for applications that require very little power, such as pocket calculators.

2.1.3. Copper indium gallium selenide (CIGS)

CIGS panels use a thin layer of copper, indium, gallium, and selenium deposited on a glass or plastic backing. The combination of these elements results in the highest efficiency among thin-panel types, though still not as efficient as crystalline silicon panels.

2.9.4. Thermo sensitive solar cells and other organ cells (DSC)

The development of these organic cells is yet to come, since it is still testing and it is not increasingly commercialized. Cell efficiency is around 10%. The tests are going in the direction of using the facade integrated systems, which has proven to be high-quality solutions in all light radiation and all temperature conditions. Also, a great potential of this technology is in low cost compared to silicon cells.
There are other types of photovoltaic technologies that are still developing, while others are to be commercialized. Regardless of the lifespan, the warranty period of today's most common commercial photovoltaic modules is 10 years at 90% power output, and 25 years at 80% power output.

2.10. Types of PV Panel and their efficiency

Table 2. 1:Types of PV technologies and their efficiency

Panel type	Efficiency
PERC	Highest (25% and more)
Monocrystalline	20% and up
Polycrystalline	15-17%
Copper indium gallium selenide (CIGS)	13-15%
Cadmium telluride (CdTe)	9-11%
Amorphous silicon (a-Si)	6-8%

Table 2. 2: Types of of solar panel with their advantages and disadvantages

Solar panel type	Advantages	Disadvantages
Monocrystalline	High efficiency and performance	Higher costs
Polycrystalline	Lower costs	Lower efficiency and performance
Thin-film	Portable and flexible	Lower efficiency and performance

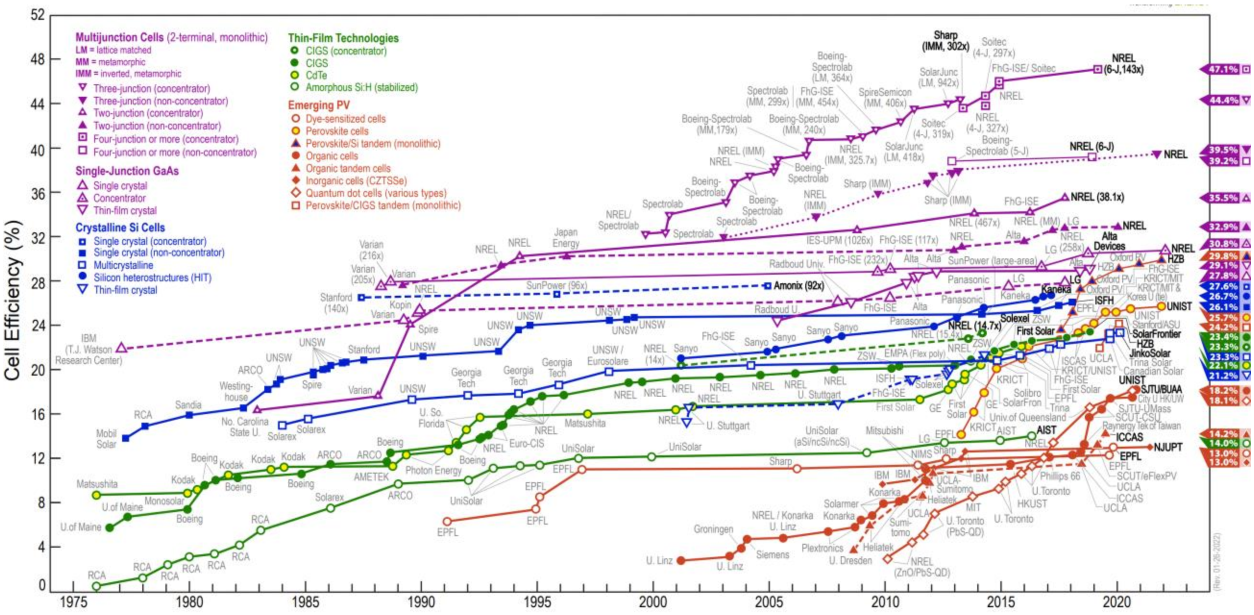

Figure 2. 12: Best research cell efficiency [67]

The figure above shows the chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present.

2.11. ADVANTAGES AND DISADVANTAGES

2.11.1.Advantages

1. Source of green energy

PV panels provide clean – green energy. During electricity generation with PV panels there is no harmful greenhouse gas emissions thus solar PV is environmentally friendly.

2. Abundance of sunlight

Energy for PV systems is gotten from solar energy which is gotten from the sun and is supplied by nature – it is thus free and abundant! Solar energy can be made available almost anywhere there is sunlight

3. High reliability and low maintenance costs

Photovoltaic systems are still highly reliable even under harsh conditions. Photovoltaic arrays ensure continuous, uninterrupted operation of critical power supplies. PV panels have no mechanically moving parts, except in cases of sun-tracking mechanical bases; consequently, they have far less breakages or require less maintenance than other renewable energy systems (e.g. wind turbines)

4. Relatively long life span

Most modules in a PV system have a warranty period of up to 25 years and remain operational even after many years.

5. Off -grid and On-grid use

PV can be grid connected, therefore adding more energy to the already generated electrical energy, this can be helpful during peak hours of electricity usage. Off grid PV system can generate electricity in rural places where electricity is not available

2.11.2.Disadvantages

1. High start-up cost

Each PV installation should be economically evaluated and compared to existing alternatives. At present, the construction cost of photovoltaic systems is relatively high, but with the reduction of photovoltaic system construction costs and the rise of traditional energy prices, photovoltaic systems will have strong economic competitiveness.

2. Available solar radiation instability

PV systems are highly weather dependent for any solar system, weather changes will greatly affect the amount of electrical energy output especially at night and on cloudy days. Although solar energy can still be collected during cloudy and rainy days, the efficiency of the solar system drops.

3. Expensive storage

Solar energy has to be used right away, or it can be stored in large batteries. These batteries, used in off-the-grid solar systems, can be charged during the day so that the energy is used at night. This is a good solution for using solar energy all day long but it is also quite expensive. The use of batteries as energy storage devices increases the footprint, cost and complexity of the system.

4. Low efficiency

The efficiency of solar panels is comparatively low compared to other renewable sources of energy. Solar panels efficiency levels are relatively (between 12%-25%)

5. Indirect pollution

Although pollution related to solar energy systems is far less compared to other sources of energy, solar energy can be associated with pollution due to usage of some toxic materials and hazardous products during the manufacturing process of solar photovoltaic systems, which can indirectly affect the environment. Nevertheless, solar energy pollutes far less than other alternative energy source

2.12. Conclusion

PV system does not just comprise of only solar panels, it comprises of other useful components such as battery for storage, converters, inverters, trackers, MPPT, etc. All these components make it function properly in the way it was designed for.

And although, PV systems have their own disadvantages, the benefits it has far outweighs its disadvantages. That’s why it has been widely adopted by the world with more research and development being done to improve on its deficiencies.

CHAPTER 3

MODELLING AND SIMULATION OF A PHOTOVOLTAIC SYSTEM

3.1. INTRODUCTION

Modeling is basic tool of the real system simulation. For modeling, it is necessary to analyse the influence of different factors on the photovoltaic cells and to take in consideration the characteristics given by the producers. The mathematical models for photovoltaic cells are based on the theoretical equations that describe the operation of the photovoltaic cells and can be developed using the equivalent circuit of the photovoltaic cells. The empirical models rely on different values extracted from the I-V characteristic of the photovoltaic cells and they approximate the characteristic equation of the solar panels using an analytical function. For the photovoltaic systems modeling, we analyse the influence of different factors on the solar panels and to consider the characteristics given by the producers. The mathematical models for PV arrays are based on the theoretical equations that describe the functioning of the PV cells and can be developed using the equivalent circuit of the PV cells. The empirical models rely on different values extracted from the I-V curve of the PV arrays and they approximate the characteristic equation of the solar panels using an analytical function.[22]

3.2. MODELLING OF A PV CELL

There are many models for a photovoltaic cell. The major ones will be discussed below

3.2.1. Different Types of Modelling for PV system

Table 3. 1: Different types of modelling of a PV system

Model	**Number of Parameters**	**Parameters**	**Precision**
Ideal	3	I_{ph}, I_{01}, n_1	Poor
Single Diode Rs Model	4	I_{ph}, I_{01}, n_1, R_s	Low
Single Diode	5	$I_{ph}, I_{01}, n_1, R_s, R_{sh}$	Okay
Two Diode Model	7	$I_{ph}, I_{01}, I_{02}, n_1, n_2, R_s, R_{sh}$	Good
Three Diode Model	9	$I_{ph}, I_{01}, I_{02}, I_{03}, n_1, n_2, n_3, R_s, R_{sh}$	Excellent

3.2.2. Ideal PV Cell

The ideal equivalent circuit of a PV cell is a current source in parallel with a single diode. The configuration of the ideal equivalent circuit of ideal solar cell with single-diode is shown in figure The equivalent model is composed from a current source which generates the photocurrent $\mathrm{I_{ph}}$ and a diode traversed by a current $\mathrm{I_d}$. The ideal PV cell model presented in figure 3.1 is the simplest PV model as the effect of series and parallel resistance are not considered.

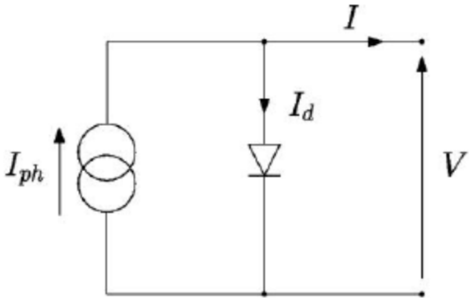

Figure 3. 1: Ideal model of a PV cell

Let $V = V_{pv}$ and $I = I_{pv}$

The current I delivered by the cell can be expressed in terms of the photocurrent $\mathrm{I_{ph}}$, the current $\mathrm{I_d}$ through the diode according to the following relationship:

$$I = I_{ph} - I_d \qquad \text{Eq 3. 1}$$

The diode current is

$$I_d = I_s\left(e^{\frac{qV_{pv}}{nkT}} - 1\right) \qquad \textit{Eq 3. 2}$$

So the output current is presented by the following nonlinear I-V equation:

$$I_{pv} = I_{ph} - I_S\left(e^{\frac{qV_{pv}}{nkT}} - 1\right) \qquad \textit{Eq 3. 3}$$

For the same irradiation and PN junction temperature conditions, the short circuit current $\mathrm{I_{sc}}$ is the greatest value of the current generated by the cell and the open circuit voltage $\mathrm{V_{oc}}$ is the greatest value of the voltage at the cell terminals. They are given by:

$$I_{sc} = I_{pv} = I_{ph} \qquad \textit{Eq 3. 4}$$

for $\mathrm{V_{pv}} = 0$

$$V_{pv} = V_{oc} = \frac{nkT}{q} ln\left(1 + \frac{I_{Sc}}{I_S}\right) \qquad \textit{Eq 3. 5}$$

for $I_{pv} = 0$

The output power is:

$$P = V_{pv}\left[I_{sc} - I_s\left(e^{\frac{qV_{pv}}{mkT}} - 1\right)\right] \qquad \text{Eq 3. 6}$$

3.2.3. Single Diode Model

The One-Diode -Model is the simplest and the most used model for PV cells. The simplified equivalent circuit of a solar cell consists of a diode and a current source which are connected in parallel. Generally, a series resistance (Rs), is introduced to the ideal cell model in order to get precise results. Although this model is simple, it reveals deficiencies when subjected to temperature variations. This model has been extended by considering a shunt resistance (Rsh). This single diode or five parameter model consists of current producer and diode with series and shunt resistances as shown in Figure 3.2. The series resistance represents the resistance (ohmic loss) offered to the current flow due to ohmic contact (metal–semiconductor contact) and resistance due to impurity concentrations along with junction depth. Leakage current across the junction signifies shunt resistance, Rsh, connected parallel to the diode. The current source generates the photo current I_{ph}, which is directly proportional to the solar irradiance G [W/m^2], ambient temperature T [ºC], and two output parameters: current Is [A] and voltage Vs [V]. The p-n transition area of the solar cell is equivalent to a diode. The characteristic equation of the one diode model could be derived from Kirchhoff's current law:

$$I_s = I_{ph} - I_d - I_{sh} \qquad \text{Eq 3. 7}$$

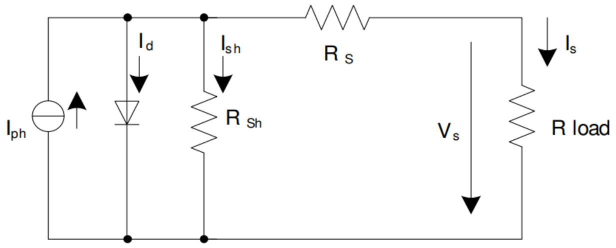

Figure 3. 2: Single diode model of a PV cell

Where:

$$I_{sh} = \frac{V_d}{R_{sh}} \qquad \text{Eq 3. 8}$$

The practical model of single solar cell is shown in figure 3. 2, in this circuit $\mathrm{R_s}$ represents series resistance of PN junction cell and $\mathrm{R_{sh}}$ represents shunt resistance which is inversely in relation with leakage current to the ground. Series resistor has great impact on the $\mathrm{I - V}$ characteristic of solar cell. $\mathrm{I_d}$ and $\mathrm{I_{sh}}$ are diode current and shunt leakage current where output terminal current I is evaluate by applying KCL in equivalent circuit of solar cell

$$I_s = I_{ph} - (I_d + I_{sh}) \qquad \text{Eq 3. 9}$$

This equation is simplified by taking sum of saturation current and shunt leakage current as I_0 and hence simplified equation is

$$I_s = I_{ph} - I_o = I_{pv} \qquad \text{Eq 3. 10}$$

Photon current is generated on absorption of solar radiation by solar cell hence photocurrent value is directly related to variation in solar irradiance and temperature and that is :

Where in this equation $\mathrm{I_{ph}}$ is rated solar current at phase. Where in this equation I_{scr} is rated solar current at nominal weather conditions $(25^0\mathrm{C}$ and $1000\mathrm{w/m^2}), \mathrm{k_i}$ is short circuit temperature coefficient. G is solar irradiance in $\mathrm{W/m^2}$ and Gr is nominal irradiance in normal weather conditions $(25°\mathrm{C}$ and $1000\mathrm{w/m^2}). \Delta\mathrm{T}$ is difference of operating temperature and nominal temperature $(\mathrm{T - T_{ref}})$. On the other hand, solar cell reverse saturation current will be calculated by:

$$I_o = I_{rs}\left(\frac{T}{T_{\mathrm{ref}}}\right)^3 exp\left[\left(\frac{q\ \mathrm{Ego}}{\mathrm{n\ K}}\right)\left(\frac{\Delta T}{T_{\mathrm{ref}}T}\right)\right] \qquad \text{Eq 3. 11}$$

Where $\mathrm{I_{rs}}$ is reverse saturation current of cell for nominal temperature and irradiance values and $\mathrm{E_{go}}$ is band-gap energy of semiconductor material. The values of $\mathrm{I_{ph}}$ and $\mathrm{I_o}$ will expand the value of I and it will be as follows:

$$I_{pv} = I_{ph} - I_0\left[exp\left(\frac{q(Vpv + IpvRs)}{nKT}\right) - 1\right] - \frac{(Vpv + IpvRs)}{Rp} \qquad \text{Eq 3. 12}$$

Since a typical PV cell produces less than 3.5 W at 0.6 V approximately, then high power can achieve by connecting many solar cells in series-parallel configuration. This configuration can be setup by connecting PV module in series and parallel connections and this group of several PV modules assembled in a PV tray is called as Solar array. Configuration of PV arrays depends on required rated voltage and current of a power plant. If $\mathrm{N_s}$ cells are connected in series and $\mathrm{N_p}$ cells are connected in parallel then equation of $\mathrm{I_{pv}}$ can be expressed as

$$I_{pv} = N_p I_{ph} - N_p I_0 \left[exp\, q\left(\frac{V_{pv} + I_{pv}R_S}{N_S AKT}\right) - 1\right] - \frac{N_p V_{pv} + I_{pv}R_S N_S}{R_p N_S} \qquad \text{Eq 3. 13}$$

Efficiency of PV module is highly sensitive to the small changes in series resistance $(\mathrm{R_s})$ and poorly sensitive to the variation in parallel resistance (R_p). Therefore, shunt resistance is assumed to be open and we can obtain a revised equation of I_{pv} by putting the value of shunt resistance as infinity $(R_{\mathrm{sh}} = \infty)$:

$$I_{pv} = N_p \left[I_{ph} - I_0 \left[exp\, q\left(\frac{V_{pv} + I_{pv}R_S}{N_S nKT}\right) - 1\right]\right] \qquad \text{Eq 3. 14}$$

Where:

$\mathrm{I_{ph}}$: photocurrent

Io: reverse saturation current of diode

$\mathrm{R_s}$: series resistance

q : electron charges $(1.602 \times 10^{-19}\mathrm{C})$

T : the temperature of p-n junction

n : diode ideality factor

k : Boltzmann constant (1.3806×10^{-23})

V : cell terminal voltage

I : cell terminal current

The produced current depends mainly upon solar radiation and the cell temperature, which is expressed by:

$$I_{ph} = \{I_{sc} + K_1(T - T_n)\}\frac{G}{1000} \qquad \text{Eq 3. 15}$$

Where:

Isc : the short circuit current at nominal condition

K1: temperature coefficient of cell's short circuit current

3.2.4. Double Diode Model

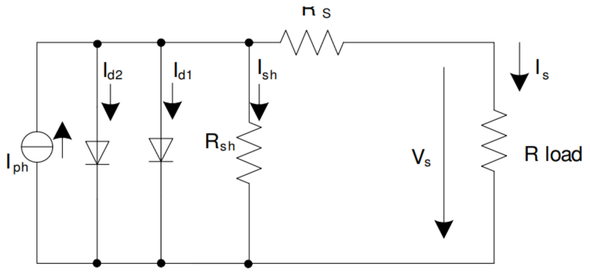

Figure 3. 3: Double diode model of a PV cell

The single diode model provides a satisfactory performance at normal conditions, and has a defect in case of low solar radiation. To overcome this problem, a two diode model is introduced, considering two diodes connected in parallel to the current source the current I_{d1}, through the first diode is the current component same as Io in case of single diode model. The current through the second diode I_{d2}, is the recombination current in space charge region. This suggests that two Shockley terms contribute to the saturation currents of a solar PV cell. Series resistance Rs, and shunt resistance Rp, are same as defined for single diode model. The double diode model of a solar PV-cell is highly accurate at low insolation levels. The double diode model can be represented by the following equation:

$$I = I_{ph} - I_{d1}\left(e^{\frac{q(V+IR_S)}{n_1kT}} - 1\right) - I_{d2}\left(e^{\frac{q(V+IR_S)}{n_2kT}} - 1\right) - \frac{V + IR_S}{R_{sh}} \qquad \text{Eq 3. 16}$$

Where: I_{d1} and I_{d2} are saturation currents of corresponding diodes. Also, n_1 and n_2 are ideality factors of diode $D1$ and $D2$ respectively, and the diode thermal voltages $(\mathrm{V_{t1}}, \mathrm{V_{t2}})$ can be expressed as following equations:

$$\begin{aligned} V_{t1} &= \frac{n_1kT}{q} \\ V_{t2} &= \frac{n_2kT}{q} \end{aligned} \qquad \text{Eq 3. 17}$$

Although the double-diode model provides a better accuracy than single-diode model, due to its complex computation, it is rarely used.

3.3. Resolution of nonlinear equation – Newton-Raphson method

There are a number of basic techniques for solving nonlinear equations. For example, there are the Substitution method, Newton-Raphson method, Bisection method, Fixed point iteration method, etc. [19]

The Newton-Raphson method is used to solve systems of nonlinear equations. It finds the roots of a nonlinear function by computing the Jacobian linearization of the function around an initial guess point, and using this linearization to move closer to the nearest zero.

One of the advantages of Newton's method is that it's not too complicated in form and it can be used to solve a variety of problems. The major disadvantage associated with Newton's method, is that the Jacobian of our equation $J(x)$, as well as its inversion has, to be calculated for each iteration. Calculating both the Jacobian matrix and its inverse can be quite time consuming depending on the size of your system is. Another problem that we may be challenged with when using Newton's method is that it may fail to converge. If Newton's method fails to converge this will result in an oscillation between points.

This method originates from the Taylor's series expansion of the function about the point x_1:

$$f(x) = f(x_1) + (x - x_1)f'(x_1) + \frac{1}{2!}(x - x_1)^2 f''(x_1) + \cdots \qquad \text{Eq 3. 18}$$

where f and its first and second order derivatives, f' and f'' are calculated at x_1. If we take the first two terms of the Taylor's series expansion, we have:

$$f(x) \approx f(x_1) + (x - x_1)f'(x_1) \qquad \text{Eq 3. 19}$$

We then set Eq 3.19 to zero (i.e., $f(x) = 0$) to find the root of the equation which gives us

$$f(x_1) + (x - x_1)f'(x_1) = 0 \qquad \text{Eq 3. 20}$$

Rearranging the (3.3) we obtain the next approximation to the root, giving us:

$$x = x_1 = x_2 - \frac{f(x_1)}{f'(x_1)} \qquad \text{Eq 3. 21}$$

Thus, generalizing Eq 3.21 we obtain Newton’s iterative method:

$$x_i = x_{i-1} - \frac{f(x_1)}{f'(x_1)} \qquad \text{Eq 3. 22}$$

where $x_i \rightarrow \bar{x}$ (as i→ ∞), and $\bar{x}$ is the approximation to a root of the function $f(x)$.

As the iterations begin to have the same repeated values i.e., as $x_i = x_{i+1} = \bar{x}$ this is an indication that $f(x)$ converges to x. Thus, x_i is the root of the function $f(x)$

Since $x_{i+1} = x_i - \frac{f(x_i)}{f\prime(x_i)}$ and if $x_i = x_{i+1}$ then

$$x_i = x_i - \frac{f(x_i)}{f'(x_i)} \qquad \text{Eq 3. 23}$$

This implies that

$$\frac{f(x_i)}{f'(x_i)} = 0 \qquad \text{Eq 3. 24}$$

and thus $f(x_i) = 0$. Another indicator that x_i is the root of the function is if it satisfies that $|f(x_i)| < \varepsilon$, where ε > 0 is the given tolerance

3.3.1. General Steps for Resolution of Nonlinear Equations using Newton Raphson−Newton-Raphson Algorithm

For a given initial estimate x_0 and a required error tolerance ε, the algorithm for the Newton-Raphson method can be written as follows:

1. $n = 0$
2. $x_{n+1} = x_n - \frac{f(x_n)}{f\prime(x_n)}$
3. If $|x_{n+1} - x_n| \leq \varepsilon$ accept $x_r \approx x_{n+1}$ then end, otherwise
4. $n = n + 1$ and go to 2

3.3.2. Newton-Raphson Used in PV

Equation 3.13 gives the equation of a single diode model of a PV cell; from the equation we can see that I_{Pv} is a nonlinear equation and we have I_{Pv} as a function of I_{Pv}. For the resolution of this nonlinear equation, Newton-Raphson method is used.

We have as equation of our model

$$I_{pv} = I_{ph} - I_0 \left[exp\left(\frac{q(Vpv + IpvRs)}{nKT} \right) - 1 \right] - \frac{(Vpv + IpvRs)}{Rp} \qquad \text{Eq 3. 25}$$

We have as input parameters I_{Pv_0}, small tolerance value ε, maximum number of iterations N_0 and as output I_{Pv}. We then code the following steps

The initial value of I_{Pv_0} is chosen as zero and value of the error ε is 0.0001.

```
1. $N = 1$
2. While $N < N_0$, do steps 3 to 6
3. Let $I_{Pv} = I_{Pv_0} - \frac{f(I_{Pv0})}{f'(I_{Pv0})}$
4. If $|I_{Pv} - I_{Pv0}| \leq \varepsilon$ print $I_{Pv}$, go to step 8
5. Let $N = N + 1$
6. Let $I_{Pv0} = I_{Pv}$
7. Print "Method failed" after N iterations
8. End
```

3.4. Modelling

3.4.1. Equations Used

Photo-current

$$I_{ph} = \left[I_{sc} + k_i \left(T - 298 \right) \right] . \frac{G}{1000} \qquad \textit{Eq 3. 26}$$

Saturation current

$$I_0 = I_{rs} . \left(\frac{T}{T_n} \right)^3 . exp \left[\frac{q \, . E_{g0} . \left(\frac{1}{T_n} - \frac{1}{T} \right)}{n \, . K} \right] \qquad \textit{Eq 3. 27}$$

Reverse saturation current

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q.V_{oc}}{n.N_s.K.T} \right)} - 1} \qquad \textit{Eq 3. 28}$$

Current through shunt resistor:

$$I_{sh} = \left(\frac{V + I.R_s}{R_{sh}}\right) \qquad Eq\ 3.\ 29$$

Output current

$$I = I_{ph} - I_0 \cdot \left[exp\left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot K \cdot N_s \cdot T}\right) - 1\right] - I_{sh} \qquad Eq\ 3.\ 30$$

3.4.2. Parameters Used

Table 3. 2: Parameters used from data sheet

Parameters	**Unit**	**Symbol**	**Value**
Photo-current	A	I_{ph}	I_{ph}
Short circuit current	A	I_{sc}	I_{sc}
Short circuit current of cell at 25°C and 1000W/m^2	A	K_i	0.0032
Operating temperature	K	T	T
Nominal temperature	K	T_n	298
Solar Irradiation	W/m^2	G	G
Electron charge	C	q	1.6×10^{-19}
Open circuit voltage	V	V_{oc}	V_{oc}
Ideality factor of diode	-	n	1.3
Boltzmann's constant	J/K	K_k	1.38×10^{-23}
Band gap energy of the semiconductor	eV	E_g	1.1
Series resistance	Ω	R_S	0.221
Parallel Resistance	Ω	R_p	

Table 3. 3: Parameters of our solar panel

Parameters	**Symbol**	**Value**
Rated power	P_{mp}	200 W
Voltage at maximum power	V_{mp}	26.4 V
Current at maximum power	I_{mp}	7.58 A
Open circuit voltage	V_{oc}	32.9 V
Short circuit current	I_{sc}	8.21 A
Total number of cells in series	N_s	54

Total number of cells in parallel	N_p	1

3.2. Model

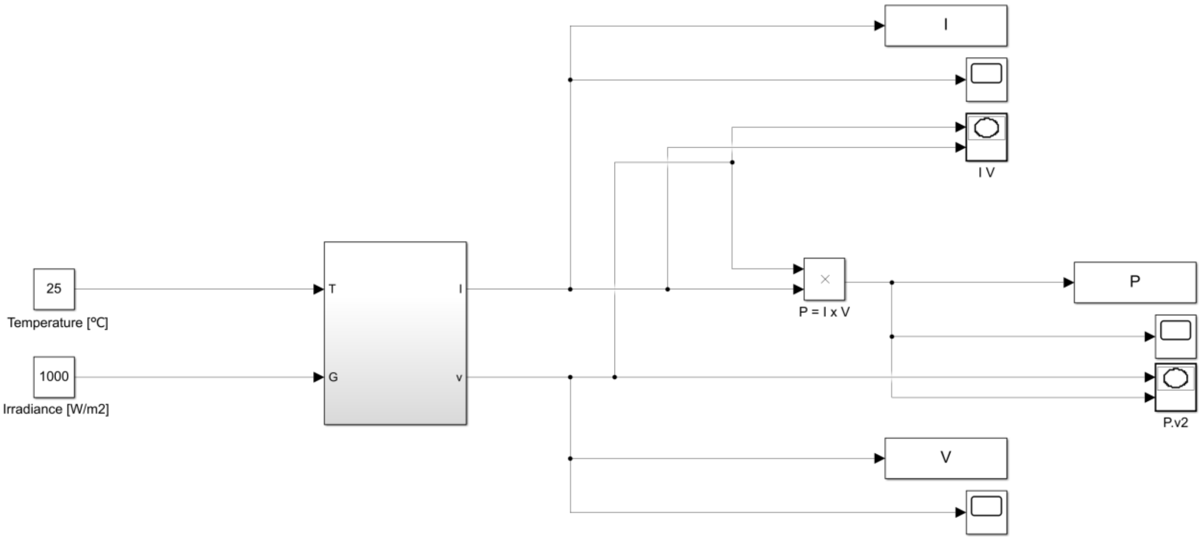

Figure 3. 4: Simulated real model of our PV cell in Simulink

For the subsystem components; please see annexe.

3.5. PV CARACTERISTIQUES

Solar Cell Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarising the relationship between the current and voltage or/and power and voltage at the existing conditions of irradiance and temperature.

3.5.1. Nominal P_V and I_V graphs

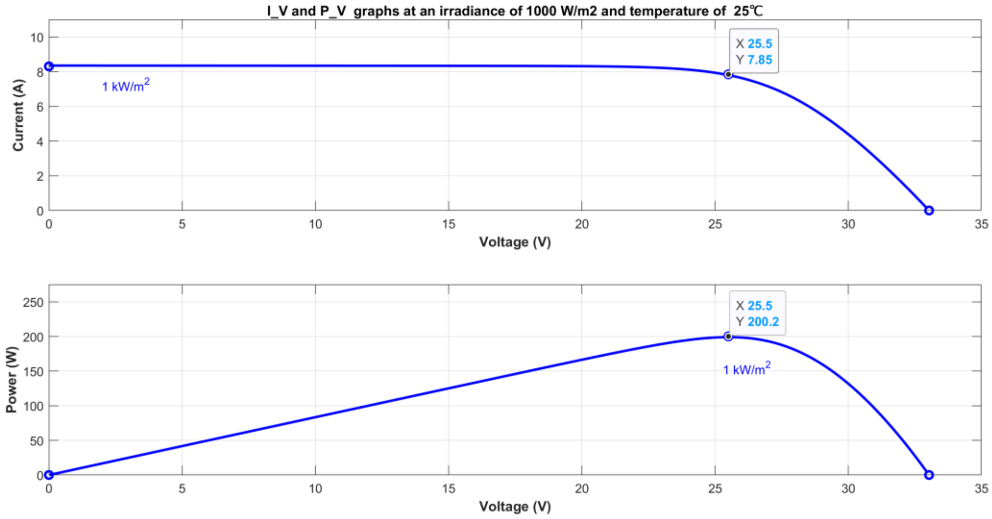

Figure 3. 5: P_V and I_V characteristic at irradiance of 100W/m^2 and temperature of 25℃

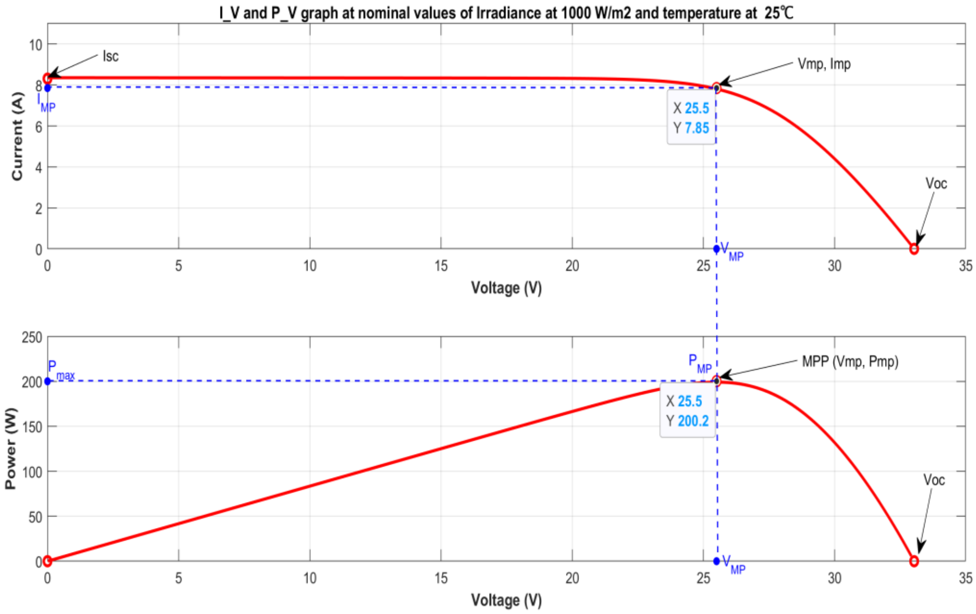

Figure 3. 6: P_V and I_V characteristic at nominal values of irradiance at 100W/m^2 *and temperature of 25 ℃ showing MPP,* V_{mp}, I_{mp}, P_{mp}, P_{max}

The curves of I_V and P_V above in figure 3.5 and 3.6 represent a standard characteristic graph of a PV panel. The simulation is done at a fixed temperature value of 25℃ and a constant irradiation of 1000W/m^2, both of which represent nominal values of temperature and irradiation consecutively. At STP (standard atmospheric conditions)

From our graph we notice that power increases until it reaches a peak point called maximum power point before it begins to decrease until it becomes zero. Current remains constant until it reaches MPP before it begins to decrease until it reaches zero.

We have a solar panel giving a maximum power of 200W at maximum power. It also has a value of 7.85 A for current and 25.5V at our maximum power point.

3.3. Effect of Varying Irradiation

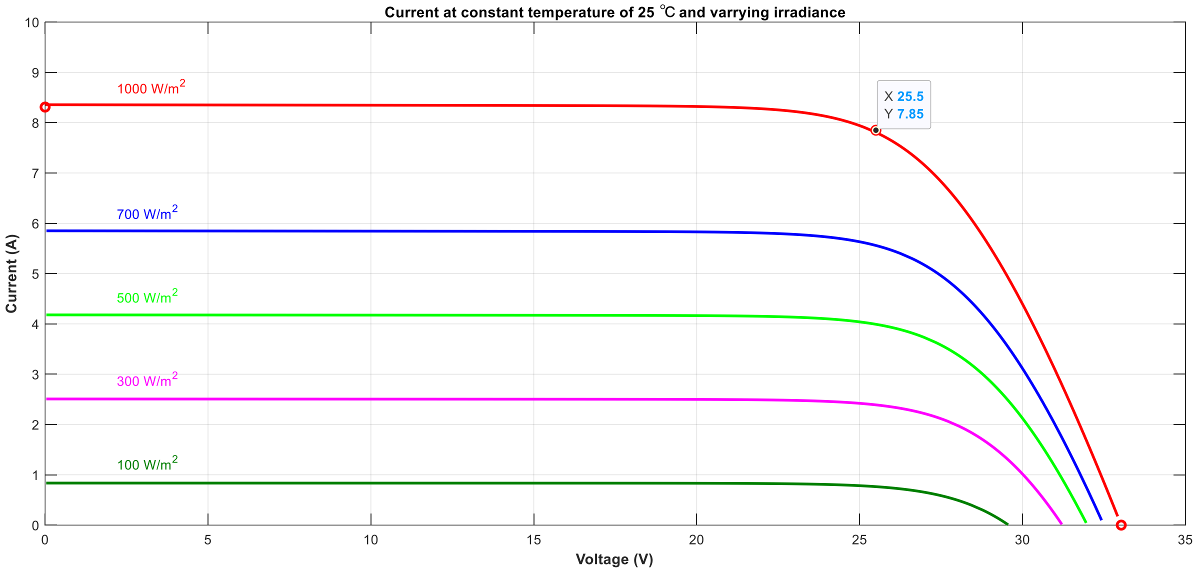

Figure 3. 7: Effect of varying irradiation on current

For constant temperature and varying irradiance there is a large change in current as our values of Isc reduces a lot with a decrease in irradiation levels, whereas Voc doesn’t vary as much as it just reduces lightly between 33V and 29V. Thus, an increase in irradiance leads to an increase in the value of Isc and vice versa.

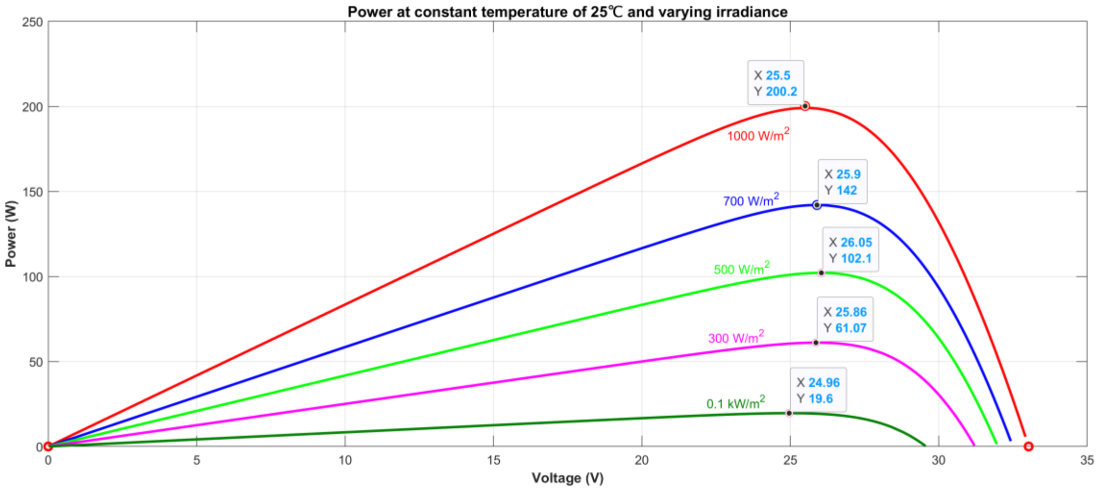

Figure 3. 8: Effect of varying irradiance on power

The figure 3.7 and 3.8 above represent the current-voltage and power-voltage characteristics of a PV panel as a function of illumination at a constant temperature of 25℃

From the various curves in the graph above we can see that with decrease in irradiation our power reduces thus reducing the value of MPP consequently. It reduces by around 5 W per decrease in irradiation.

We can deduce that the current is directly proportional to the irradiation contrary to the tension which varies a little (almost constant)

3.4. Effect of Varying Temperature

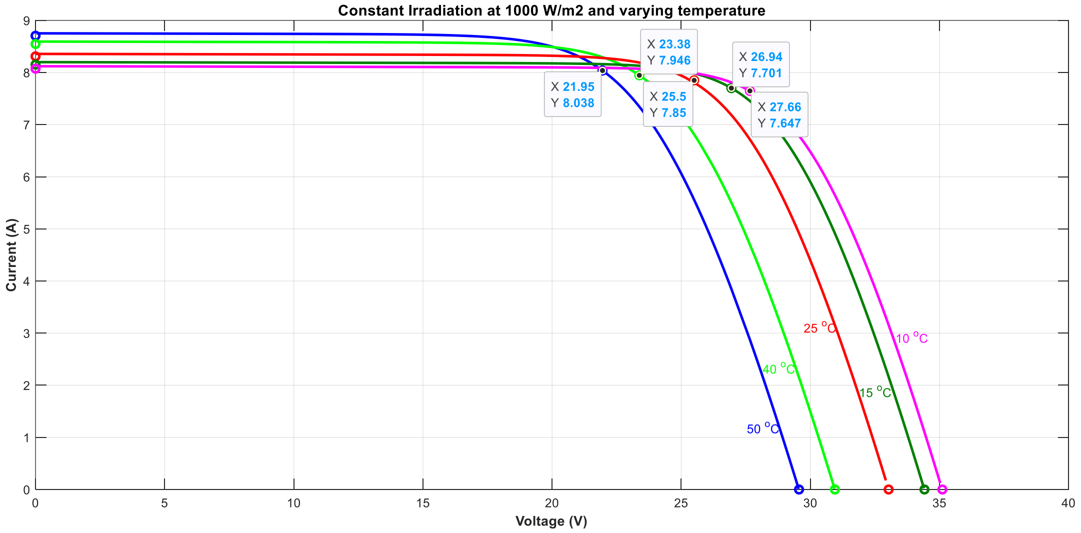

Figure 3. 9: Effect of varying temperature on I-V curve

Varying temperature with a constant irradiation has little to no effect on our current as the values of Isc is almost constant, always around 8A. While voltage decreases with every increase in temperature

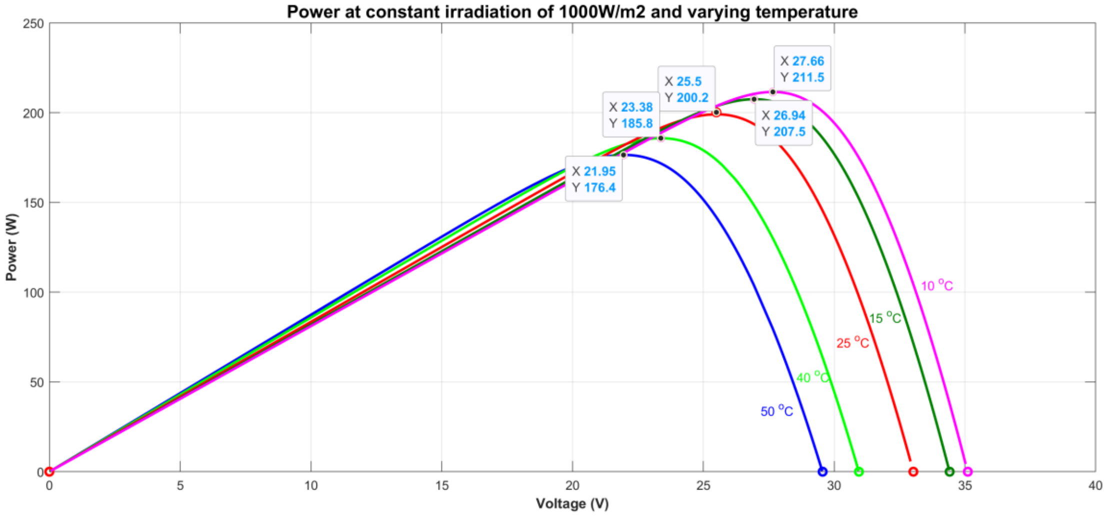

Figure 3. 10: Effect of varying temperature on P-V curve

From our curves, the parameter most affected by an increase or decrease in temperature is the open-circuit voltage Voc. The impact of varying temperature is shown in the figure above.

The open circuit voltage decreases considerably when the temperature increases.

The increase in temperature also results in the decrease of maximum power

It confirms the well-known relation between the efficiency of PV installation and the temperature yielding to a decrease of the produced power with the increase of the temperature.

In conclusion, a PV panel produces maximum power at a high value of irradiance and a correspondingly low temperature.

3.5. Comparison with Manufacturer’s model (Real Model)

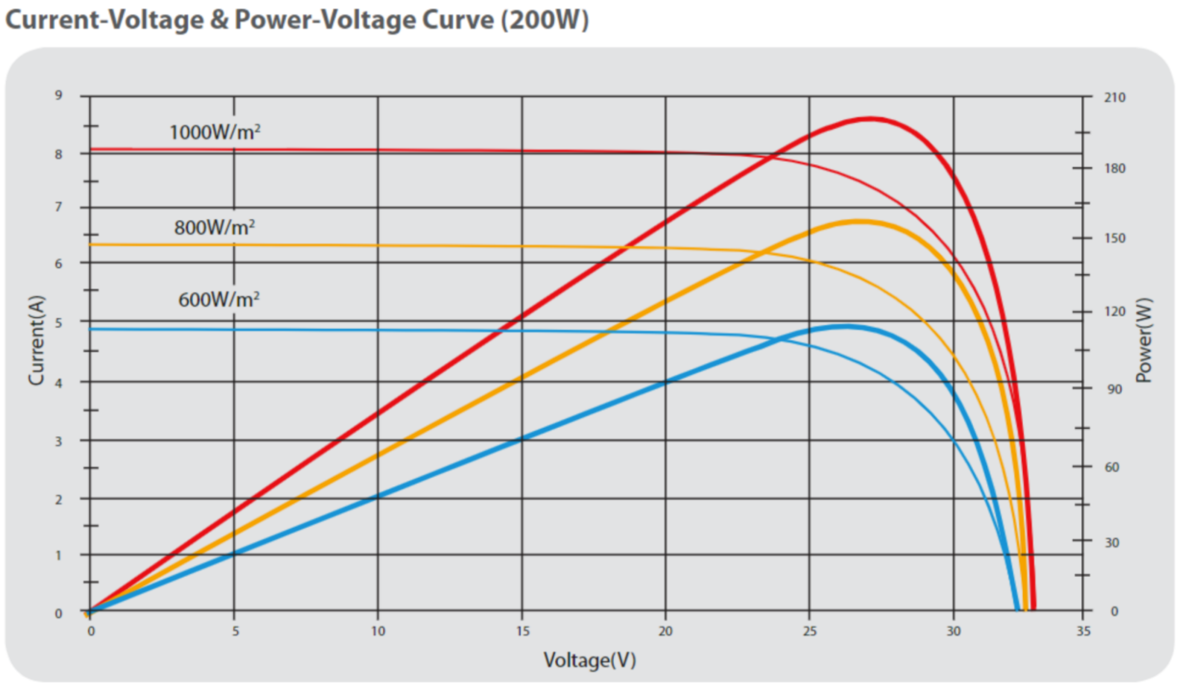

Figure 3. 11: Manufacturer provided P-V and I-V graphs

After extensive comparison of the values of Voc, Isc, Imp, Vmp, Pm and MPP between our simulated model curves and the characteristics given by the manufacturer for different variation of Irradiation and Temperature. We note that our different graphs are very similar with little to no difference. With this we can confirm that our modelled PV is the same as a real model.

3.6. Solar array parameters

The main parameters that are used to characterise the performance of solar cells are the peak power Pmax, the short-circuit current density Isc, the open-circuit voltage Voc, and the fill factor FF. These parameters are determined from the I-V and P-V characteristics as illustrated in figure 3.12 below

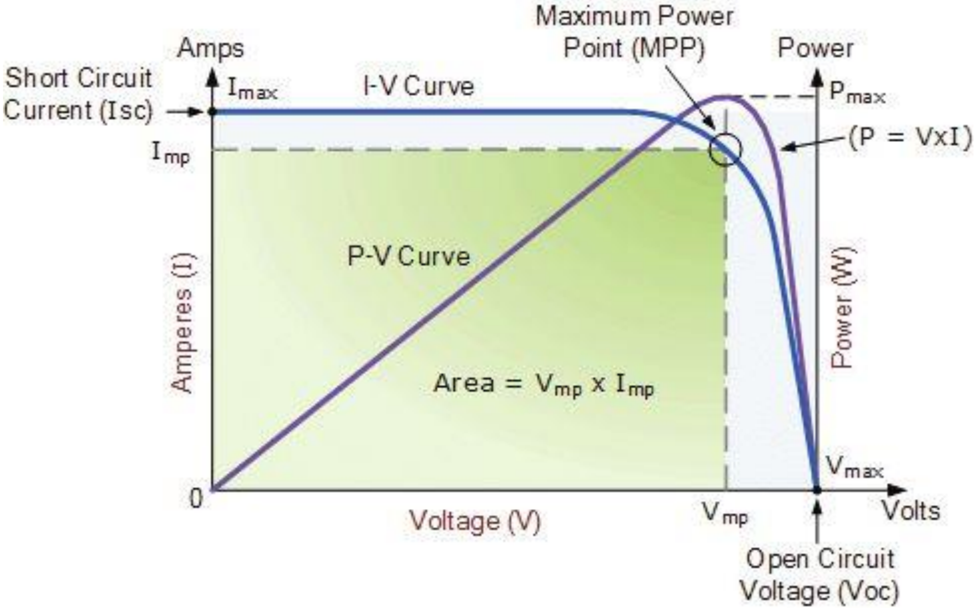

Figure 3. 12:I-V and P-V characteristics of a typical solar cell

3.6.1. V_{OC} – open-circuit voltage

This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition), it is the voltage at which no current flows through the external circuit This value is much higher than Vmp which relates to the operation of the PV array which is fixed by the load and It is the maximum voltage that a solar cell can deliver. This value depends upon the number of PV panels connected together in series. The open-circuit voltage. Voc corresponds to the forward bias voltage, at which the dark current compensates the photocurrent. Voc depends on the photo-generated current density and can be calculated using an equation. The equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \qquad \textit{Eq 3. 31}$$

V_{OC} decreases with temperature. If temperature changes, I_0 also changes.

3.6.2. I_{SC} –short-circuit current

The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition) i.e., it is the current that flows through the external circuit when the electrodes of the solar cell are short circuited. It occurs when the voltage across the device is zero. This value is much higher than Imp which relates to the normal operating circuit current. The value of short circuit current depends on cell area, solar radiation on falling on cell, cell technology, etc. The short-circuit current of a solar cell depends on the photon flux density incident on the solar cell, which is determined by the spectrum of the incident light. For a standard solar cell measurement, the spectrum is standardised to the AM1.5 spectrum. In order to remove the dependence of the solar cell area on Isc, often the short-circuit current density is used to describe the maximum current delivered by a solar cell. The maximum current that the solar cell can deliver strongly depends on the optical properties of the solar cell, such as absorption in the absorber layer and reflection.

where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively. the equation for the short-circuit current density can be approximated as:

$$J_{SC} = qG(L_n + L_p) \qquad Eq\ 3.\ 32$$

The short circuit current, I_{SC}, is the short circuit current density, J_{SC}, times the cell area:

$$I_{sc} = J_{sc} \times A \qquad Eq\ 3.\ 33$$

3.6.3. MPP – maximum power point

This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Imp x Vmp. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp). The maximum power point will be discussed more in the subsequent chapter.

3.6.4. FF–fill factor

The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage multiplied by the short-circuit current, (V_{OC} x I_{SC}) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8. The fill factor is the area shaded in green in figure 3.7

The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. Graphically, the

FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the I-V curve.

$$FF = \frac{P_{mp}}{I_{sc}V_{oc}} = \frac{V_{mp}\, I_{mp}}{I_{sc}V_{oc}} \qquad \textit{Eq 3. 34}$$

3.7. Conversion Efficiency – η

The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell. Improving this conversion efficiency is a key goal of research and helps make PV technologies cost-competitive with conventional sources of energy.

3.7.1. Factors affecting efficiency

Not all of the sunlight that reaches a PV cell is converted into electricity. In fact, most of it is lost. Multiple factors in solar cell design play roles in limiting a cell's ability to convert the sunlight it receives. Designing with these factors in mind is how higher efficiencies can be achieved.

- Wavelength—Light is composed of photons—or packets of energy—that have a wide range of wavelengths and energies. The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.

- Recombination—One way for electric current to flow in a semiconductor is for a "charge carrier," such as a negatively-charged electron, to flow across the material. Another such charge carrier is known as a "hole," which represents the absence of an electron within the material and acts like a positive charge carrier. When an electron encounters a hole, they may recombine and therefore cancel out their contributions to the electrical current. Direct recombination, in which light-generated electrons and holes encounter each other, recombine, and emit a photon, reverses the process from which electricity is generated in a solar cell. It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.

- Temperature—Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes. Since much of the sunlight shining on cells becomes heat, proper thermal management improves both efficiency and lifetime.
- Reflection—A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti-reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

3.7.2. Calculation

The conversion efficiency is calculated as the ratio between the maximal generated power and the incident power. The irradiance value P_{in} of 1000 W/m2 for the AM1.5 spectrum has become a standard for measuring.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mp}\, V_{mp}}{P_{in}} = \frac{I_{sc}\, V_{oc}\, FF}{P_{in}} \qquad Eq\ 3.\ 35$$

We know P_{in} is the product of light irradiation (E, in W/m^2), all under standard test conditions (STC) and the surface of photovoltaic solar cells (A_C in m^2).

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mp}\, V_{mp}}{E\, A_c} = \frac{I_{sc}\, V_{oc}\, FF}{E\, A_c} \qquad Eq\ 3.\ 36$$

3.8. Conclusion

In this chapter, we have modelled a solar cell using mathematical equations for different number of parameters. Using our equations, we have simulated an ideal and a real PV cell using Simulink. From there we have seen the effect of varying temperature and irradiation on our characteristic curves. Which leads us to conclude that; to have a high value of maximum power and consequently a high power, a solar panel must function at high value of irradiance and a correspondingly low temperature

CHAPTER 4

DC/DC CONVERTERS

4.1. INTRODUCTION

A DC-DC converter, simply known as DC converters are circuits that converts high frequency power using rapid switching, inductors and capacitors to smoothen noise in DC voltage circuits. It can be considered the DC equivalent of an AC transformer with continuously variable turn’s ratio. It is primarily used to step-up or step-down voltage from dc voltage sources.

DC-DC converters are used in traction motor control in automobiles, in voltage regulators and DC current source inverters. Before the advent of power semiconductors, DC voltage supply conversion for low power application was done by using a vibrator along-side a transformer and a rectifier. This implies that the DC voltage was converted to AC voltage and again rectified and filtered to convert to DC voltage again. For high power applications, a generator of desired voltage was driven by an electric motor to obtain the required DC voltage. Such means of stepping up or down DC voltage incurred huge expenses and the processes were highly cumbersome to begin with. With the invention of power electronic integrated circuits and solid-state switch mode circuits, these processes became cheaper and more efficient.

The DC-DC converters are driven by PWM, whereby a high frequency pulse signal is used to turn on and off the electronic switches, thus controlling the converter voltage. There are different types of conversion method such as electronic, linear, switched mode, magnetic, capacitive, etc.

DC/DC converters are used, within the framework of a photovoltaic system, to generate the desired voltages and currents as well as for the adaptation of photovoltaic panels (continuous source) with different loads to achieve the maximum power transfer. The source and load can be capacitive (voltage source) or inductive (current source) in nature. The converter is chosen according to the load to be supplied and their role in this case is to maintain the operating point at or close enough to the MPP for all operating conditions (radiation, temperature, load characteristic, etc).[34]

4.2. DC-DC Converters topology

There different kinds of DC-DC converters, some major one includes: the buck converter, boost converter, buck-boost converter, cuk converter, fly-back converter, forward converter, push-pull converter, full bridge converter, half bridge converter, current fed converter, multiple output converters etc.

For photovoltaic applications, there are 3 most common types of non- isolated converters chopper reduction (or buck), chopper uplift (or boost), buck-boost chopper.[6]

4.2.1. Buck

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while drawing less average current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor). A typical buck converter circuit is shown in figure 4.1

Figure 4. 1: Buck converter circuit

The input voltage source is connected to a controllable solid-state device which operates as a switch. The solid-state device can be a Power MOSFET or IGBT. Thyristors are not used generally for DC-DC converters because to turn off a Thyristor in a DC-DC circuit requires another commutation which involves using another Thyristor, whereas MOSFET and IGBT can be turned off by simply having the voltage between the gate and source terminals of a Power MOSFET, or, the GATE and COLLECTOR terminals of the IGBT go to zero.

The second switch used is a diode. The switch and the diode are connected to a low-pass LC filter which is appropriately designed to reduce the current and voltage ripples. The load is a purely resistive load.

The input voltage is constant and the current through load is also constant. The load can be seen as current source.

The controlled switch is turned on and off by using Pulse Width Modulation (PWM). PWM can be time based or frequency based. Frequency based modulation has disadvantages like a wide range of frequencies to achieve the desired control of the switch which in turn will give the desired output voltage. This leads to a complicated design for the low-pass LC filter which would be required to handle a large range of frequencies. Time based Modulation is mostly used for DC-DC converters. It is simple to construct and use. The frequency remains constant in this type of PWM modulation.

The Buck converter has two modes of operation. The first mode is when the switch is on and conducting.

MODE I: Switch is ON, Diode is OFF

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Figure 4. 2: Switch ON, diode off – Buck converter circuit

The voltage across the capacitance in steady state is equal to the output voltage.

Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF}. We define the time period, T, as and the switching frequency,

The duty cycle D is:

$$D = \frac{T_{on}}{T} \qquad \text{Eq 4. 1}$$

We can analyse the Buck converter in steady state operation for this model using Kirchhoff's voltage law (KVL)

$$V_{in} = V_L + V_0 \qquad \text{Eq 4. 2}$$

$$V_L = L\frac{dI_L}{dt} = V_{in} - V_0 \qquad Eq\ 4.\ 3$$

$$\frac{dI_L}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{\Delta I_L}{D\ T} = \frac{V_{in} - V_0}{L} \qquad Eq\ 4.\ 4$$

Since the switch is closed for a time T_{ON} = DT we can say that Δt = DT from

$$(\Delta I_L) = \frac{V_{in} - V_0}{L}\ DT \qquad Eq\ 4.\ 5$$

MODE II: Switch is OFF, Diode is ON

Here, the energy stored in the inductor is released and is ultimately dissipated in the load resistance, and this helps to maintain the flow of current through the load. But for analysis we keep the original conventions

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Figure 4. 3: Switch OFF, diode ON–Buck converter circuit

$$0 = \ V_L + V_0 \qquad Eq\ 4.\ 6$$

$$V_L = L\frac{dI_L}{dt} = -V_0 \qquad Eq\ 4.\ 7$$

$$\frac{dI_L}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{\Delta I_L}{D\,T} = \frac{V_{in} - V_0}{L} \qquad \text{Eq 4. 8}$$

Since the switch is open for a time $T_{OFF} = T - T_{ON} = T - DT\ = (1 - D)T$
We can say that $\Delta T = (1 - D)T$

$$(\Delta I_L)_{open} = \frac{-V_0}{L}(1 - D)T \qquad \text{Eq 4. 9}$$

The net change of the inductor current over anyone complete cycle is zero, therefore;

$$(\Delta I_L)_{closed} + (\Delta I_L)_{open} = 0 \qquad \text{Eq 4. 10}$$

$$\frac{V_{in} - V_0}{L}DT\ +\ \frac{-V_0}{L}(1 - D)T = 0 \qquad \text{Eq 4. 11}$$

$$\frac{V_0}{V_{in}} = D \qquad \text{Eq 4. 12}$$

4.2.2. Buck-Boost

This static converter makes it possible to have a variable DC voltage higher or lower than the fixed input voltage. During the first conduction phase, from 0 to αT where α is the duty cycle D, the controlled switch is closed. The diode is non-conductive and the inductor stores the energy supplied by the input generator. During the second phase, from αT to T, the controlled switch opens and the diode becomes conductive. The inductance returns its energy to the load. In continuous conduction and knowing that the average value at the terminals of the inductance is zero, we have:

$$V_{PV}DT = V_{DC}(1 - D)T \qquad \text{Eq 4. 13}$$

Which gives:

$$V_{DC} = \frac{D}{(1 - D)}V_{PV} \qquad \text{Eq 4. 14}$$

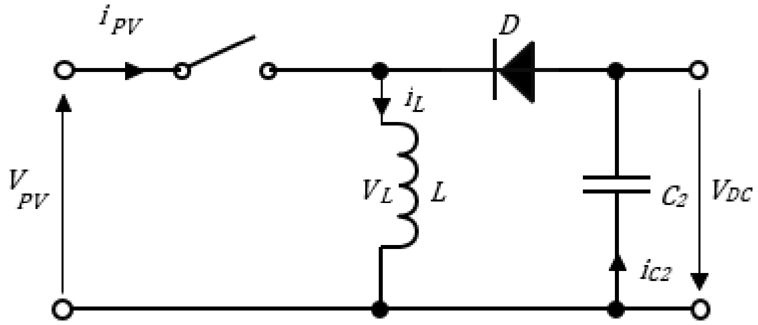

Figure 4. 4: Buck-boost converter circuit

Depending on the value of the duty cycle D, the average output voltage can be higher or lower than the input voltage:

- ✓ when D > 0.5, the buck-boost chopper functions as a boost chopper.
- ✓ When D < 0.5, the buck-boost chopper functions as a buck chopper (step-down).

In this project, we will focus mainly on the boost converter which play a key role in stepping up the DC voltage and also in tracking the maximum power point

4.3. Boost converter

4.3.1. Introduction

Boost converters are a type of DC-DC converters that boost which means to increase, elevate or shoot up the input voltage to a specified or particular output voltage according to our specific needs and use. Boost converters are also referred to as step up chopper. The figure below shows the circuit diagram of a Boost converter:

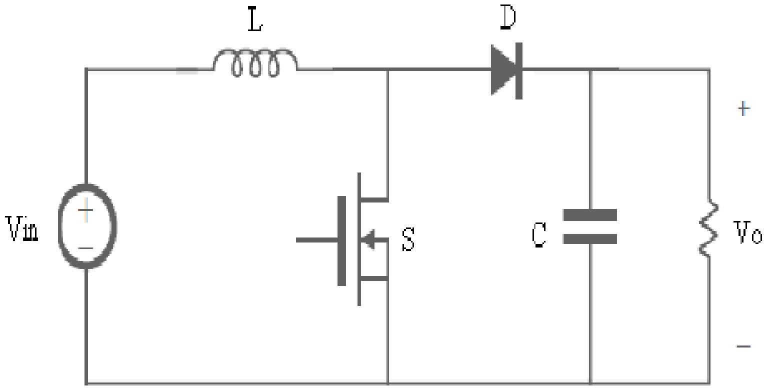

Figure 4. 5: Circuit diagram of a boost converter

As with reference to the figure above, we see how the components are connected in this case the input voltage supply is connected to the associated inductance, then the solid-state device that acts as a switch is connected across the supply, while the second switch used could be a diode. The diode is connected to a capacitor, as is the load, and the two are connected in parallel.

The inductance that is connected to the input source runs a constant input current, therefore, the boost converter is considered the constant current input source and the load can be considered as a constant voltage source. The controlled switch turns on and off using pulse width modulation (PWM) which can be time based or frequency-based. The frequency-based modulation has disadvantages such as a wide frequency range to achieve the desired control of the switch, which in turn gives the desired output voltage. Time-based modulation is mainly used for DCDC converters. It is easy to set up and use. With this type of PWM modulation, the frequency remains constant. The boost converter has two modes of operation that are mode switch on and mode switch off.[41]

4.3.2. Switch ON mode

During the mode switch ON, Diode is off

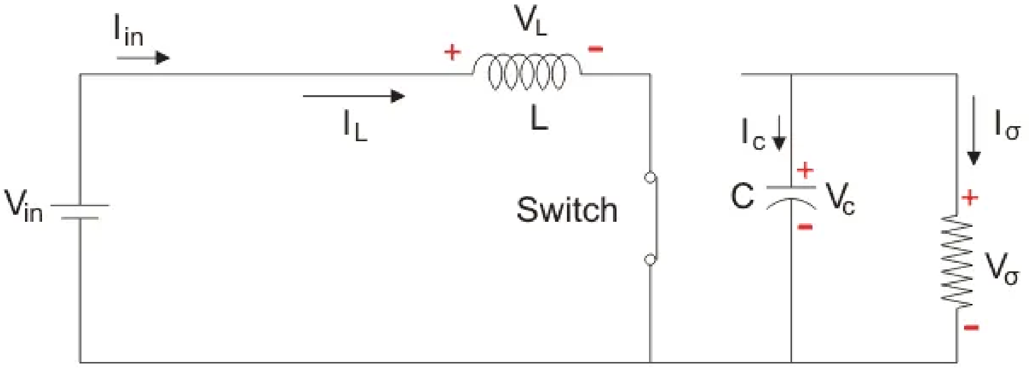

Figure 4. 6: Boost converter with switch on and diode off

The Switch on mode refers to when the switch is ON and therefore represents a short circuit that ideally offers zero resistance to the flow of current. Hence all the current will flow through the switch and back to the DC input source when the switch is ON. We assume that the switch is on for a time T_{ON} and is off for a time T_{OFF}. Henceforth we define the time period, T, as:

$$T = T_{ON}+T_{OFF} \qquad \text{Eq 4. 15}$$

Giving us the switching frequency as:

$$f = \frac{1}{T} \qquad \text{Eq 4. 16}$$

We can also define the duty cycle given s:

$$D = \frac{T_{ON}}{T} \qquad \text{Eq 4. 17}$$

Using Kirchhoff's Voltage Law, we analyse the Boost converter in steady space operation.

$$V_{in} = V_L \qquad \text{Eq 4. 18}$$

$$V_L = L\frac{di_L}{dt} = V_{in} \qquad \text{Eq 4. 19}$$

$$\frac{di_L}{dt} = \frac{\Delta_{iL}}{\Delta t} = \frac{\Delta_{iL}}{DT} = \frac{V_{in}}{L} \qquad \text{Eq 4. 20}$$

As the switch is closed for a certain period of time $T_{ON} = D_T$ we can then say that $\Delta t = DT$.

$$(\Delta i_L)_{closed} = \left(\frac{V_{in}}{L}\right) DT \qquad \text{Eq 4. 21}$$

While performing the analysis of the Boost converter, we have to keep in mind that during the analysis of the Boost converter we place prominence on the fact that:

- The current flowing through the inductor is continuous and to achieve this we select an appropriate value of L.
- During the ON state, the current flowing through the inductor steady-state increases from a value with a positive slope to a maximum value and then later drops back to its initial value with a negative slope. Therefore, the complete cycle of the net change of the inductor current is zero.

4.3.3. Switch OFF mode

During the mode switch OFF, Diode is on.

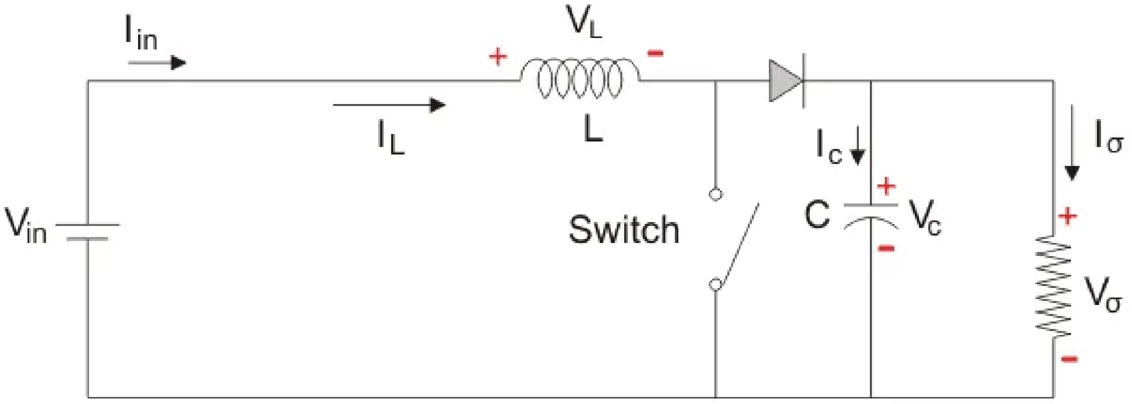

Figure 4. 7: Boost converter when switch is OFF and diode is on

In the course of this mode, the polarity (which is the direction of the magnetic or electric field) of the inductor is reversed. The energy stored in the inductor is released and eventually dissipated in the load resistance, helping the current flow through the load in the same direction and also increasing the output voltage since the inductor is now acting as a source in conjunction with the input source. However, for the analysis, we keep the original conventions for analysing the circuit with the use of Kirchhoff's Voltage Law.

In the second mode and using Kirchhoff's Voltage Law, we analyse the Boost converter in steady space operation

$$V_{in} = V_L + V_o \qquad \text{Eq 4. 22}$$

$$V_L = L\frac{di_L}{dt} = V_{in} - V_o \qquad \text{Eq 4. 23}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta_t} = \frac{\Delta i_L}{(1-D)L} = \frac{V_{in} - V_o}{L} \qquad \text{Eq 4. 24}$$

Since the switch is open for a certain amount of time:

$T_{OFF} = T - T_{ON} = T - DT = (1-D)T$

We can therefore say;

$\Delta t = (1-D)T$

$$(\Delta i_L)_{open} = \left(\frac{V_{in} - V_o}{L}\right)(1-D)T \qquad \text{Eq 4. 25}$$

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

$$\left(\frac{V_{in} - V_o}{L}\right)(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0 \qquad \textit{Eq 4. 26}$$

$$(1 - D)T + \left(\frac{V_o}{L}\right)DT = 0 \qquad \textit{Eq 4. 27}$$

$$\frac{V_o}{V_{in}} = \frac{1}{1 - D} \qquad \textit{Eq 4. 28}$$

4.3.4. State space model of boost converter

We know that $V_0 = V_c$

During the ‘ON’ state, the inductor is charged through V_{in} defined in Eq 4.29. There is no current flow to the capacitor and resistor in this state, where i_L is zero as defined in Eq4.30.[40]

$$V_{in} = L\,\frac{di_L}{dt} \qquad \textit{Eq 4. 29}$$

$$0 = C\,\frac{dV_C}{dt} + \frac{V_C}{R} \qquad \textit{Eq 4. 30}$$

The state derivative of $x_1{}'$ and $x_2{}'$ in Eq 4.31 and Eq 4.32 can be obtained by rearranging Eq 4.29 and 4.30. The state space matrix *A* and *B* in Eq 4.31 for boost converter in the ‘ON’ state can be formulated using 4.31 and 4.32.

$$x_1' = \frac{1}{L}\,V_{in} \qquad \textit{Eq 4. 31}$$

$$x_2' = -\,\frac{x_2}{RC} \qquad \textit{Eq 4. 32}$$

$$\begin{bmatrix} x_1{}' \\ x_2{}' \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\dfrac{1}{RC} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix} V_{in} \qquad \textit{Eq 4. 33}$$

When Boost converter enters the ‘OFF’ state condition, where the equivalent circuit is similar to Buck converter in the ‘ON’ state. Therefore, state space matrix *A* and *B* for Boost converter ‘OFF’ state is:

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \qquad \textit{Eq 4. 34}$$

The average of the boost converter state space A and B matrix for its ‘ON’ and ‘OFF’ state can be formulated with the account of switching duty cycle d. The average A and B matrix are shown in equations 4.36 and 4.38 respectively.

$$\bar{A} = A_{(ON)}d + A_{(OFF)}(1-d) \qquad \textit{Eq 4. 35}$$

$$\bar{A} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} d + \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} (1-d) = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \qquad \textit{Eq 4. 36}$$

$$\bar{B} = B_{(ON)}d + B(1-d) \qquad \textit{Eq 4. 37}$$

$$\bar{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} d + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} (1-d) = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \qquad \textit{Eq 4. 38}$$

To complete the boost converter model, the average matrix of equations 4.36 and 4.38 are substitute into state space modelling equation of $x' = Ax + Bu$

The completed boost converter state space model is shown in Eq 4.39.

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \qquad \textit{Eq 4. 39}$$

To obtain the output state of V_C and i_L, the output state space for C and D matrix is shown in Eq 4.40.

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u_1 \qquad \textit{Eq 4. 40}$$

4.4. PV array connected to boost and load

Before our PV panel is connected to grid we need to test if our components are functioning properly. In this section we'll be checking out our boost by connecting a load of 100 Ω and make sure we have an elevated voltage as final output.

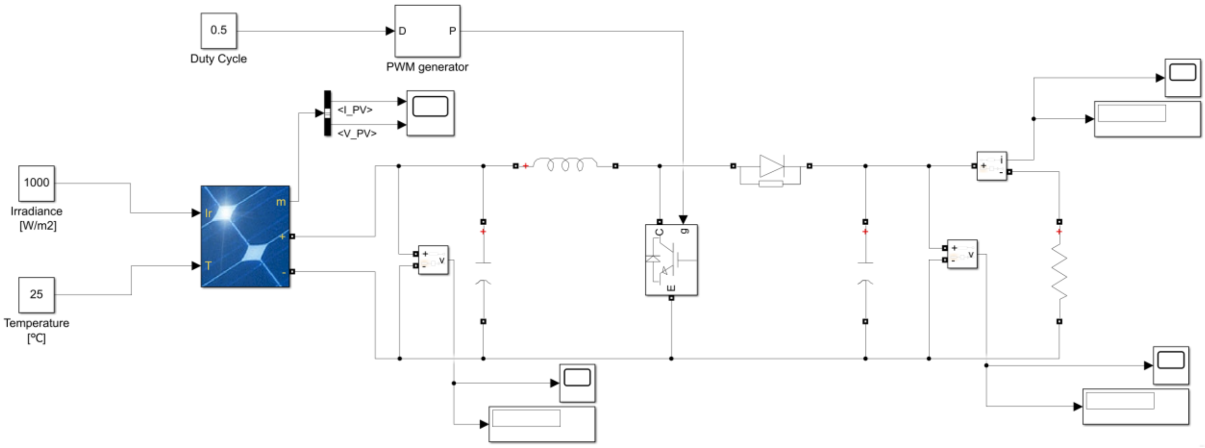

Figure 4. 8: PV array connected to boost converter and load

We obtain the following graphs

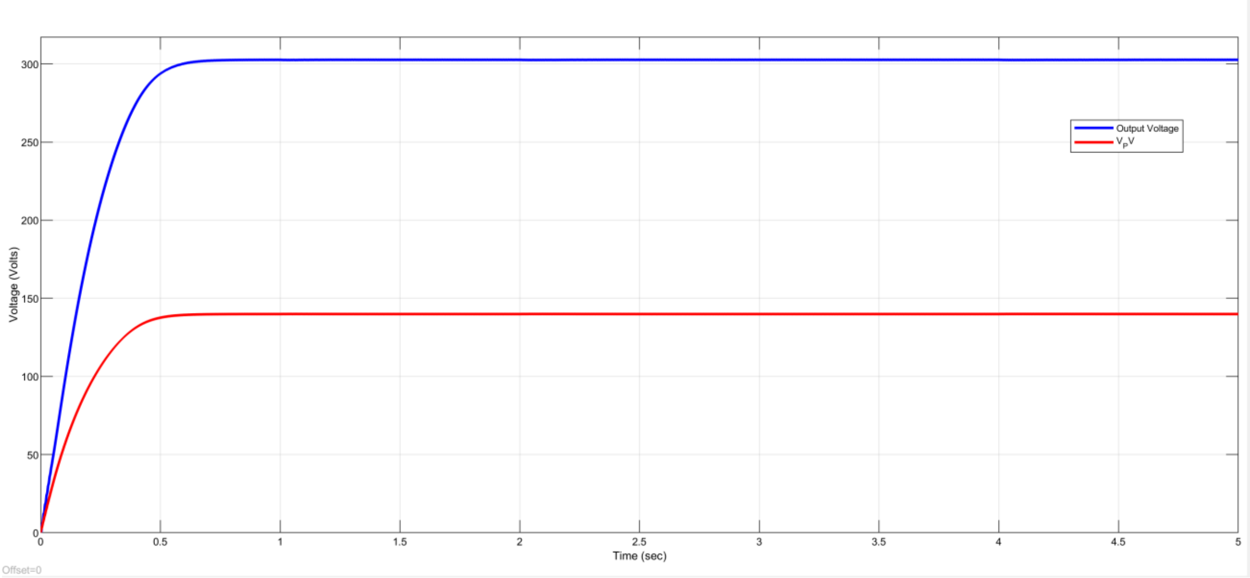

Figure 4. 9: Voltage before and after boost

Our output voltage is greater than the input voltage which is the voltage supplied by the PV panel, this confirms proper functioning of our converter. Our boost converter has a very fast response time, reaching steady state at about 0.6 seconds. There was no oscillation before reaching steady, meaning the choice of values of our capacitance and inductance is good. The voltage increases steadily before attaining steady state.

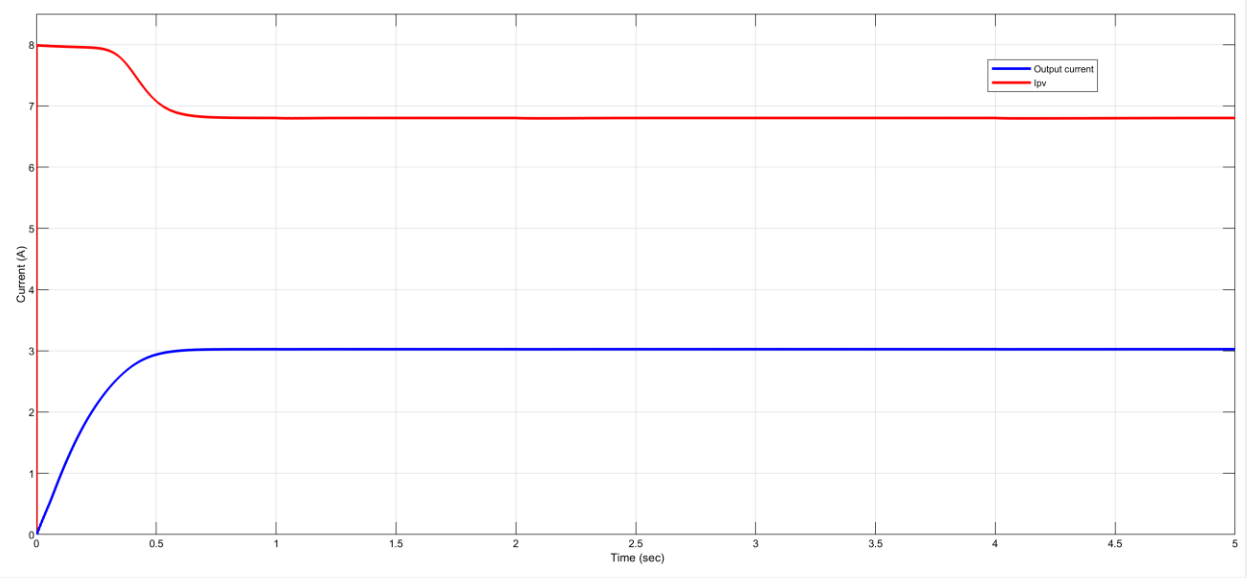

Figure 4. 10: Current before and after boost

There is a decrease in current from our PV panel from 9A in the beginning to 6.9A at steady state, because we have an increase in voltage.

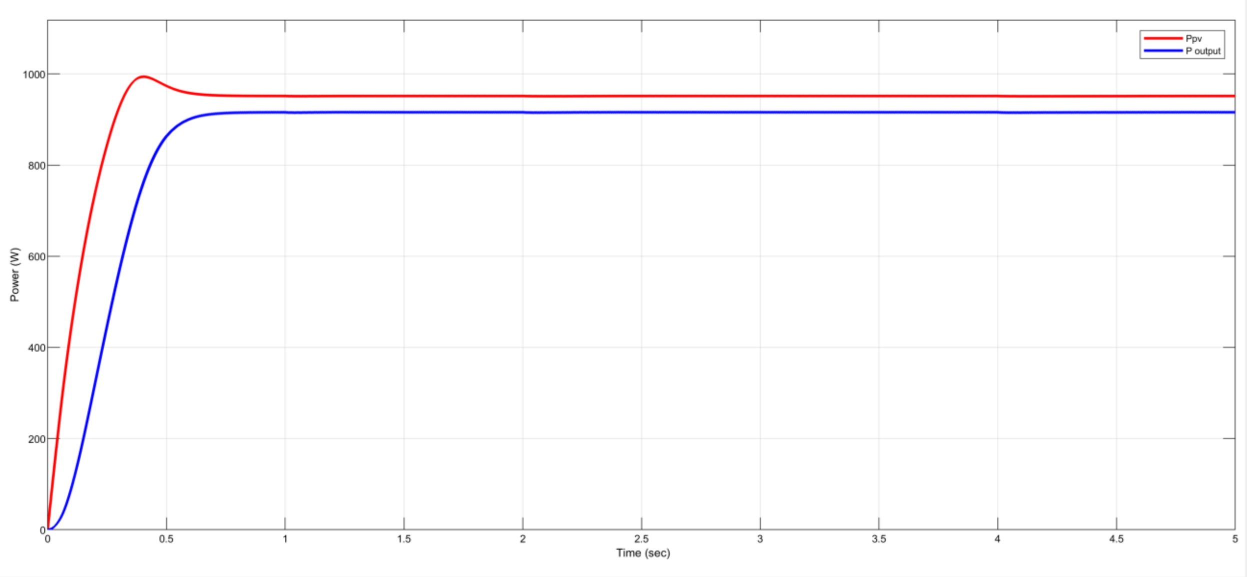

Figure 4. 11: Power before and after boost

From the above figures of current and voltage we can conclude that our boost functions normally as it raised our output voltage to 300V from 140V output from the PV panel.

Whilst doing that, the current reduced from around 6.9 A in the steady state to 3A, this is due to the law of conservation of energy. As input power must be equal to output power. Thus, when voltage increases, current must decrease and vice versa

Output power is a little less than input power, this is due to losses in our converter. Because its efficiency is less than 100%, and also because some power is lost in our load of 100Ω.

4.5. Conclusion

In this chapter, we have modelled a boost converter to be used in conjunction with our solar array. We have tested and confirmed that it functions properly before its use in subsequent chapters.

CHAPTER 5

MPPT TECHNIQUES

5.1. Introduction

Solar photovoltaic has been subjected to efficiency improvement since the invention of the photovoltaic cell. Once the photovoltaic cell is made in the laboratory or industry, its efficiency improvement measures cannot be taken. However, solar trackers and Maximum Power Point Trackers (MPPT) are used to getting the maximum out of the solar modules. Varying atmospheric condition changes all the parameters (Pmax, Vmax, Imax, Voc, Isc) of the solar cell. Solar trackers are used in orienting the PV modules towards the sun to maximize the solar irradiation. MPPT is used to let the photovoltaic cell function at its maximum power point by properly adjusting the duty cycle of the converter. Various MPPT algorithms can be implemented according to the situation and our needs.

In order to solve the energy problem and achieve the maximum possible efficiency, the design of all elements of the photovoltaic system must be optimized. MPPT controllers are used to increase this efficiency. Such controllers are becoming an indispensable element in photovoltaic systems. Various MPPT control schemes have been developed since the 1970s, ranging from simple techniques such as MPPT based on voltage and current feedback to advanced MPPT based on power feedback such as the Perturbation and Observation (PandO) technique or incremental conductance. Recently, MPPT based intelligent control schemes such as Fuzzy Logic (FL), Artificial Network (ANN) and Particle Swarm Optimization (PSO) have been introduced.

In this chapter, we are interested in the application of MPPT controls in particular Incremental Conductance, sliding mode and P&O on photovoltaic systems. Interest in these controls is increasing due to its ease of development and its wide range of uses. in automation or power electronics. All these algorithms have their own characteristics regarding complexity, convergence speed, step response, steady state oscillations about MPP and required electronics equipment. The goal of these controls is to bring the operation of the system closer to the MPPT.[11]

5.2. Maximum Power Point

The maximum power point (MPP) represents the bias potential at which the solar cell outputs the maximum net power. That is, it is the voltage at which the photovoltaic modules produce maximum power. The MPP voltage can drift depending on wide range of variables including the irradiance intensity, device temperature, and device degradation. Therefore, an important aspect of PV module engineering is in creating systems to track the MPP continuously with time, in order to maximize the net power output. Ideally, the MPP tracking (MPPT) system should also account for unforeseeable events such as imperfect operating conditions and individual cell failures.

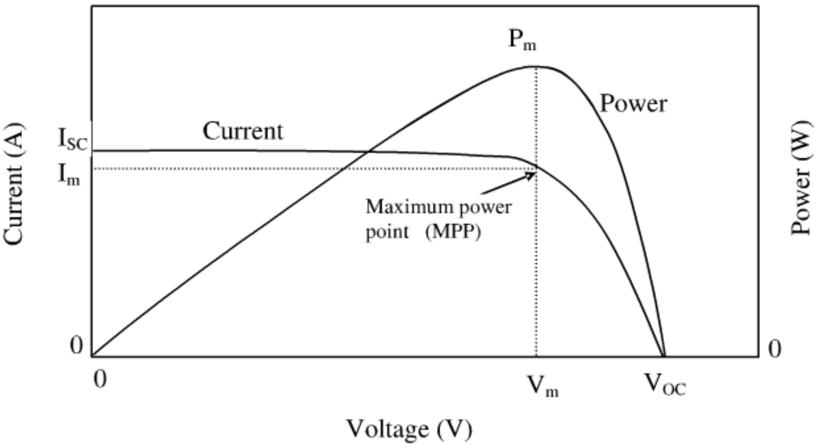

Figure 5. 1: MPP on I-V and P-V curves

5.3. Maximum Power Point Trackers (MPPT)

The power supplied by a photovoltaic system from one or more photovoltaic cells depends on the irradiation, the temperature and the current drawn from the cells. In addition, daily solar radiation shows abrupt fluctuations throughout the day. Under these conditions, the MPP (Maximum Power Point) of the photovoltaic system changes continuously; Consequently, the operating point of the photovoltaic system must change in order to maximize the energy generated.

Therefore, an MPPT (Maximum Power Point Tracking) technique is used to keep the operating point of the PV array at its MPP. The MPPT is used to get the most performance out of these systems. Applications such as feeding electricity into the grid, charging batteries or driving an electric motor benefit from MPPT. In these applications, it can happen that the load requests more energy than the photovoltaic system can supply. In this case, an energy conversion system is used to maximize the energy of the photovoltaic system.

There are many different approaches to maximizing the performance of a PV system, ranging from using simple voltage ratios to more complex analysis. MPPT control is a very powerful tool to optimize the photovoltaic power system and ensure smooth operation in changing weather conditions. It generally relies on the DC-DC converter duty cycle variation to follow the MPP.

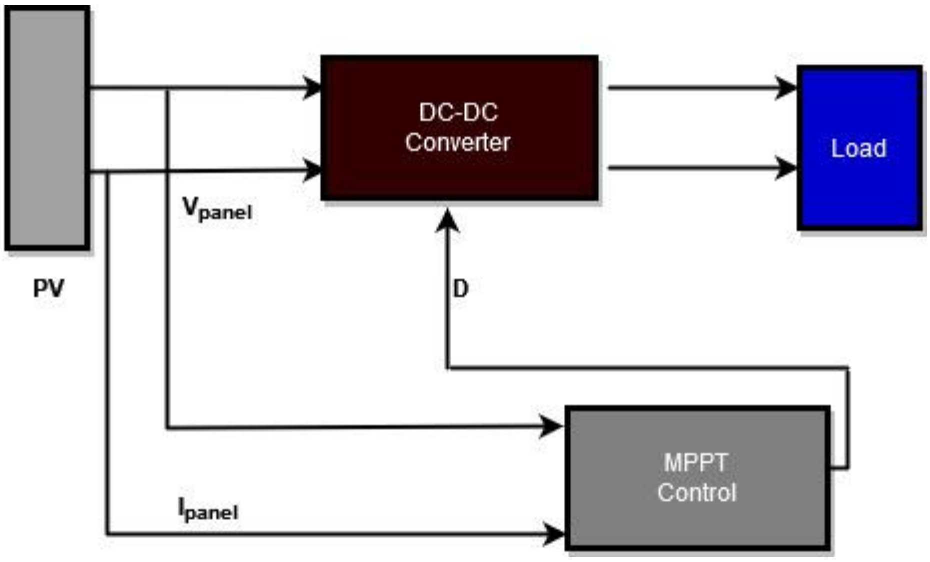

Figure 5. 2:Chain diagram of an MPPT controlled solar panel

Maximum Power Point Tracking (MPPT) controllers witness much attention as an important optimization field of PV systems. These controllers employ different algorithms and they vary in their efficiency, performance, modernity, complexity, and tracking speed

5.4. Classification of MPPT Techniques

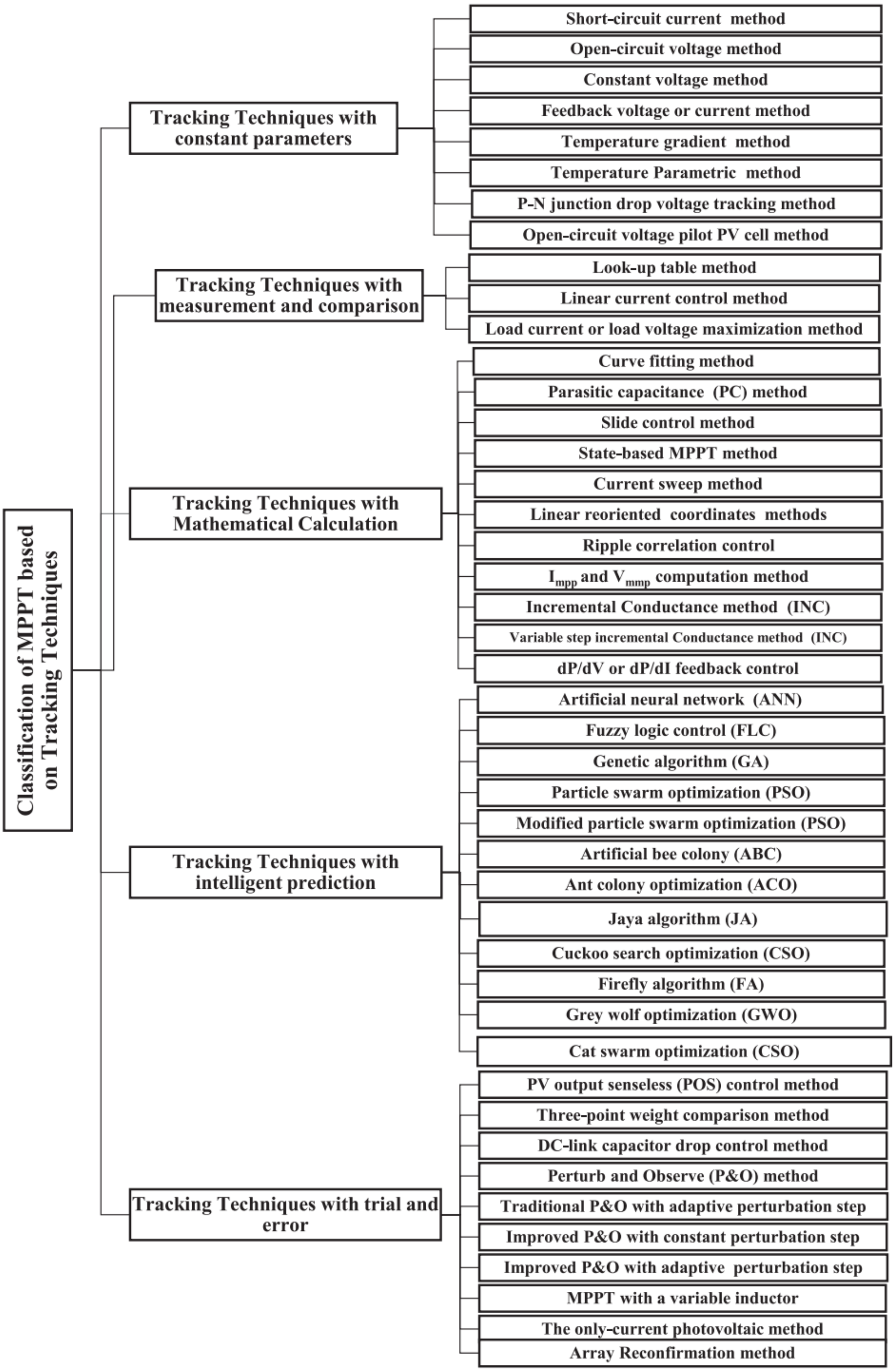

Figure 5. 3: Classification of MPPT based on tracking techniques

5.5. Perturb and Observe (P&O)

5.5.1. Principle

The perturb and observe(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.[18]

5.5.2. Algorithm

The perturbation and observation algorithm (commonly referred to as P&O) is of the "hill" climbing type" (English word that means "climbing a hill"). It is the most used in practice because of its ease of implementation. This algorithm aims to operate the system at its maximum power by incrementing or decrementing the operating point voltage and observing the effect of this disturbance on the power delivered by the PV panel. According to this observation, the algorithm decides on the act to be done during the next iteration. Four case scenarios for P&O are considered in and summarized in the Table 5.1 below

Table 5. 1: Table of principle of the P and O method

Case N°	**ΔV**	**ΔP**	$\frac{\Delta P}{\Delta V}$	**Sense of pursuit**	**Control Action**
1	+	+	+	good	Increment $V_{ref} = V_{ref} + \Delta V$
2	-	-	+	bad	Increment $V_{ref} = V_{ref} + \Delta V$
3	+	-	-	bad	Decrement $V_{ref} = V_{ref} - \Delta V$
4	-	+	-	good	Decrement $V_{ref} = V_{ref} - \Delta V$

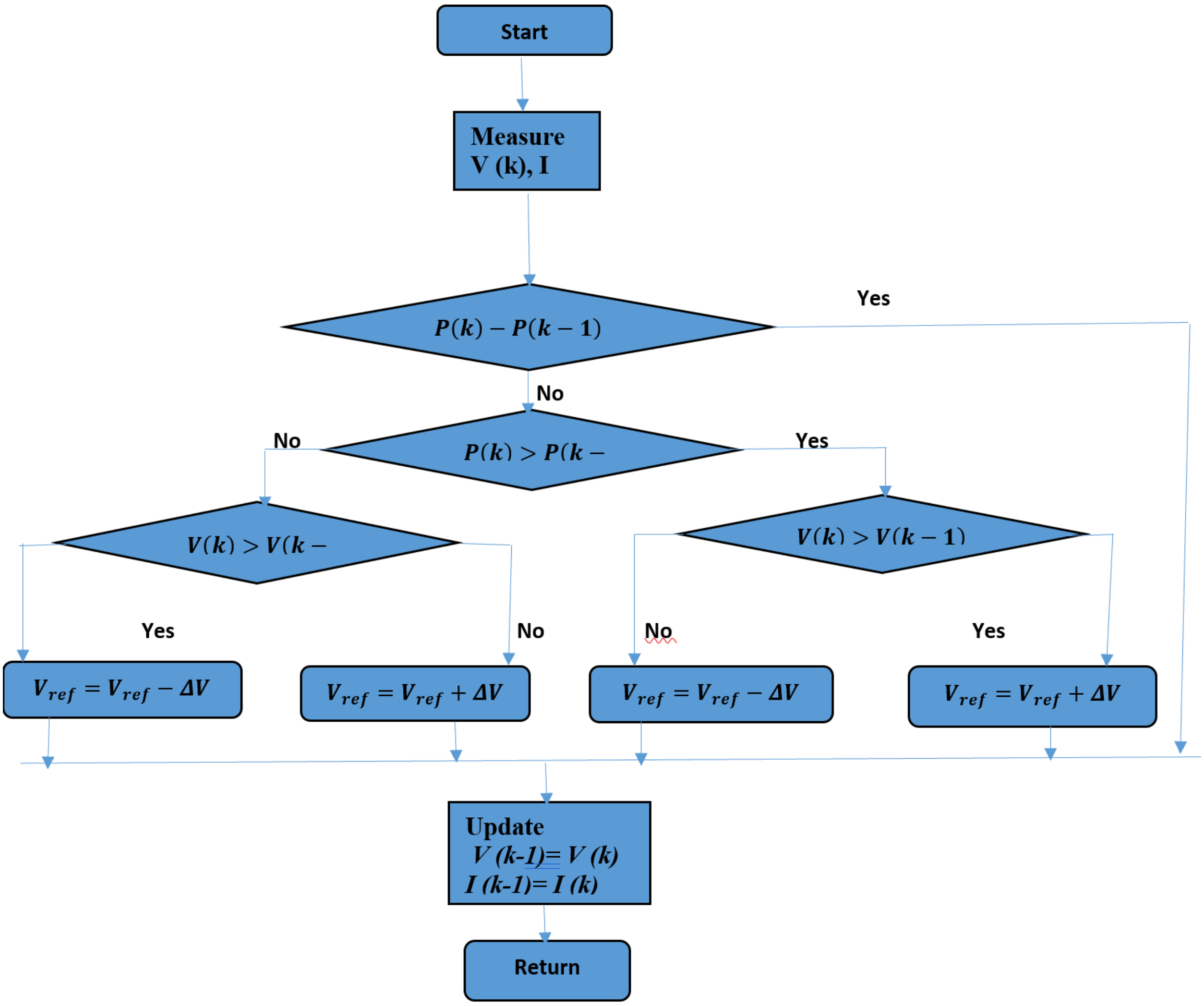

Figure 5. 4: Flowchart of P&O algorithm

5.5.3. Limitations of P&O algorithm

The P&O algorithm has the advantage of precision and speed of reaction. It allows determining the point of maximum power for sunshine and a temperature or a level of feature degradation. The problem with this algorithm includes

- 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.

- Another common problem in P&O algorithms is 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.
- The oscillation around the PPM under normal operating conditions. It should be noted that these oscillations can be reduced if we set a low incrementation step but at the expense of convergence time. So, a compromise must be made between accuracy and speed. when choosing this
- The poor convergence of the algorithm in the case of sudden variations of the temperature and/or sunlight

5.6. Incremental Conductance

5.6.1. Principle

The conductance incremental algorithm (Inc Cond), is also one of the Hill Climbing techniques where the MPPT command tries to raise the operating point of the PV panel along the P-V. The incremental conductance algorithm detects the slope of the P–V curve, and the MPP is tracked by searching the peak of the P–V curve. This algorithm uses the instantaneous conductance $G = \frac{I}{V}$ and the incremental conductance $\Delta G = \frac{\Delta I}{\Delta V}$ for MPPT[36]. This algorithm requires knowledge of the initial value of the operating point (V_{ref}) and the update step reference voltage (ΔV). The maximum power is obtained when the derivative of the power of the PV with respect to the voltage vanishes i.e., $\frac{\Delta P}{\Delta V} = 0$

$$\frac{dP}{dV} = V\frac{dI}{dV} + I \approx \mathrm{V}\frac{\Delta I}{\Delta V} + I \qquad \textit{Eq 5. 1}$$

5.6.2. Algorithm

By comparing the conductance and the increment of the conductance, three positions of the functioning point can be distinguished:

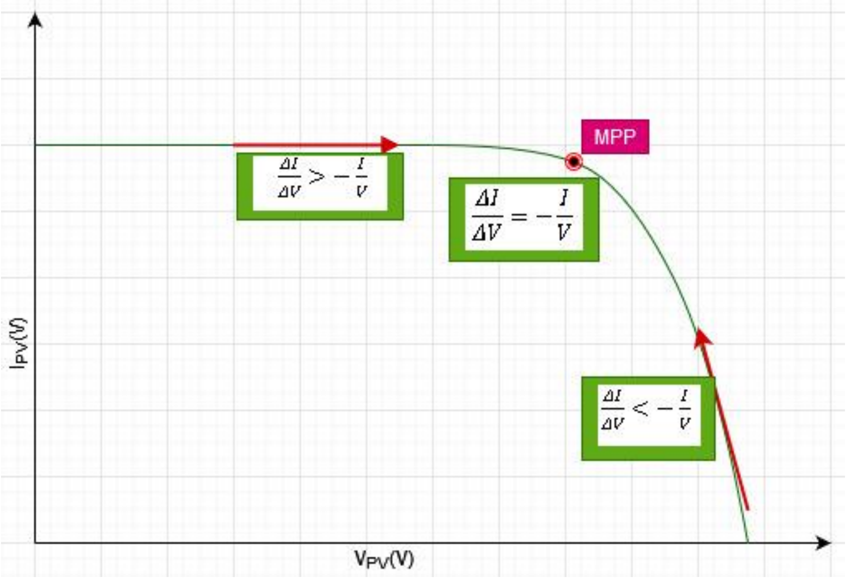

Figure 5. 5: Operating characteristic of incremental conductance method

If $\frac{dP}{dV} = 0 \implies \frac{\Delta I}{\Delta V} = -\frac{I}{V}$, at the MPP

If $\frac{dP}{dV} > 0 \implies \frac{\Delta I}{\Delta V} > -\frac{I}{V}$, to the left of the MPP

If $\frac{dP}{dV} < 0 \implies \frac{\Delta I}{\Delta V} < -\frac{I}{V}$, to the right of the MPP

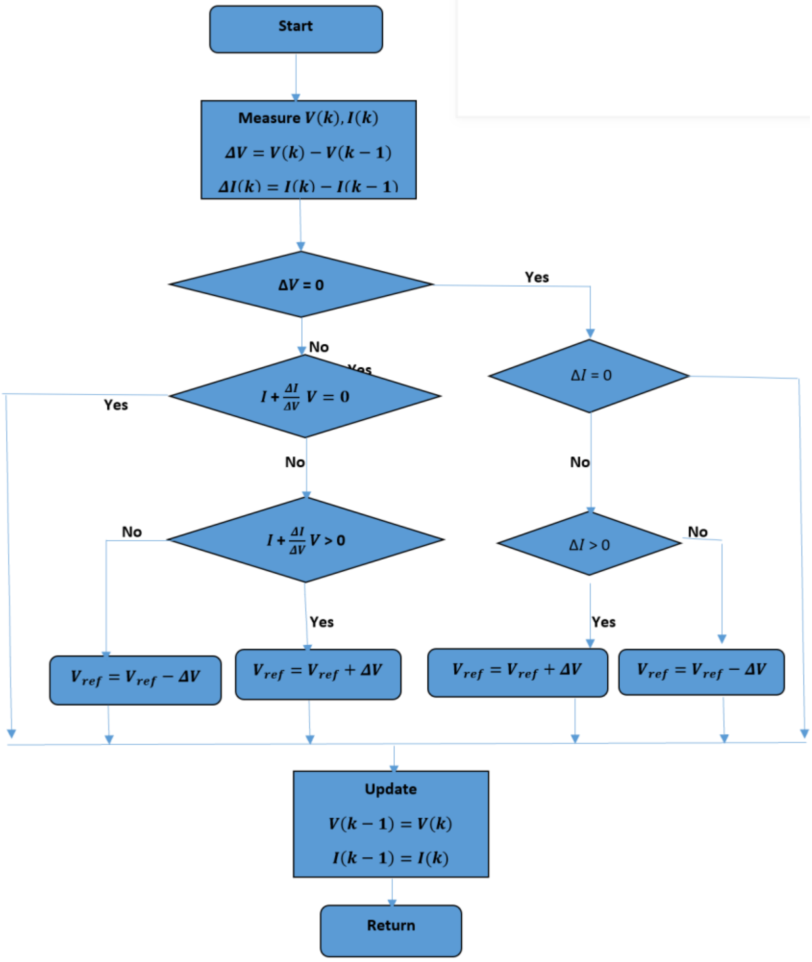

Figure 5. 6: Flowchart of incremental conductance algorithm

5.7. Sliding mode control

5.7.1. Variable Structure system

A variable structure system is a system whose structure changes during its operation. It is characterized by the choice of a structure and a switching logic. It admits a representation by differential equations of the type:

$$\dot{x} = \begin{cases} f_1(x) & \text{if the condition } 1 \text{ is verified} \\ f_n(x) & \text{if the condition } n \text{ is verified} \end{cases} \qquad Eq\ 5.2$$

Where f_n are functions belonging to a set of subsystems.

5.7.2. Theory of sliding modes

In systems with variable structures with sliding mode, the state trajectory is brought towards a surface, then with the help of the switching law, it is forced to remain in the vicinity of this surface. The latter is called the sliding surface and the movement along which it occurs is called the sliding movement. This command is applied to the systems described by the following equation (we limit ourselves to the case of two operating modes n=2):

$$x = f = \begin{cases} f^{+}(x, u^{+}) & si(x,t) > 0 \\ f^{-}(x, u^{-}) & si(x,t) < 0 \end{cases} \qquad \textit{Eq 5. 3}$$

The control law vector fields u+ and u− are defined by:

$$u = \begin{cases} u^{+} & si(x,t) > 0 \\ u^{-} & si(x,t) < 0 \end{cases} \qquad \textit{Eq 5. 4}$$

Where (x,t) is the switching (or sliding) surface.

The switching surface S_0 is defined as follows:

$$S_0 = \{x(t)\ for\ S(x,t) = 0\} \qquad \textit{Eq 5. 5}$$

5.7.3. Principle of sliding mode control

The technique of sliding mode control consists in bringing the state trajectory of a system towards the sliding surface and switching it using an appropriate switching logic until the point of equilibrium. This trajectory consists of three distinct parts.[23]

Convergence mode

In the reaching mode, the variable to be tuned moves from any initial point x0 in the phase plane and approaches the switching surface S(x)=0. This mode is characterized by the control law and the convergence criterion.

Sliding mode

For sliding mode, the state variable reaches the sliding surface and tends towards the origin of the phase plane. The dynamics in this mode is characterized by the choice of the sliding surface (x).

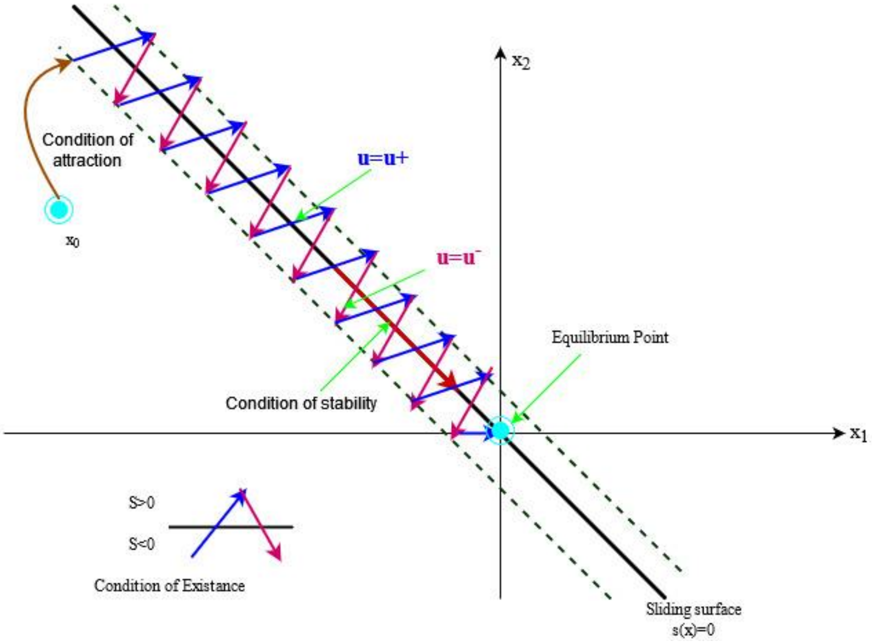

Figure 5. 7: Principle of control of sliding mode

First theorem: Let V(x) be a function called the Lyapunov function which satisfies the following conditions:

$$\begin{cases} V(0) = 0 \\ V(x) > 0 \quad \forall x \neq 0 \\ \dot{V}(x) \leq 0 \quad \forall x \neq 0 \end{cases} \qquad \text{Eq 5. 6}$$

If these three conditions are satisfied, x=0 is a stable equilibrium point. If moreover $\dot{V}(x)$<0 (Strictly negative) for ∀x≠0, the point x=0 is asymptotically stable.

The Lyapunov function is generally used to guarantee the stability of nonlinear systems. It can take the following form:

$$V(x) = \frac{1}{2} S^2(x) \qquad \text{Eq 5. 7}$$

Thus, its derivative verifies the following equation:

$$\dot{V}(x) = S(x)\dot{S}(x) \qquad \text{Eq 5. 8}$$

Sliding mode control design

The design of the sliding mode control involves three main and complementary stages:

- Choice of the sliding surface $S(x)$,
- Establishment of the conditions for its existence and convergence,
- Determination of the control law u.

Choice of sliding surface

The choice of sliding surface relates to the number and shape needed. These two factors depend on the application and the intended purpose. In general, for a system defined by the following state equation:

$$\dot{x}(t) = f(x,t) + g(x,t)u(t) \qquad \textit{Eq 5. 9}$$

The surface S(x) represents the desired dynamic behaviour of the system. A form of general equation to determine the slip surface, which ensures the convergence of a variable towards its desired value is given by:

$$S(x) = \left(\frac{d}{dt} + \boldsymbol{\beta}\right)^{r-1} e(x) \qquad \textit{Eq 5. 10}$$

With:

- $e(x)$: deviation of the variable to be tuned $e(x)$=$xref-x$,
- β: positive constant,
- r: relative degree, equal to the number of times the output must be derived to cause the command to appear. Thus, we find:
    - ✓ for r=1, $S(x)$=$e(x)$,
    - ✓ for r=2, $S(x)$=$\beta e(x)$+$\dot{e}(x)$.
- S(x)=0 is a linear differential equation whose unique solution is e(x)=0.

Existence of sliding mode

This condition represents the criterion allowing the dynamics of the system to converge towards the sliding surface and remain there even in the face of disturbances. That is ensured when the Lyapunov function is decreasing. Thus, it suffices to ensure that its derivative is negative which is equivalent to:

$$S(x)\dot{S}(x) < 0 \qquad \textit{Eq 5. 11}$$

Calculation of the control law:

After the choice of the sliding surface and the convergence criterion, it is necessary to determine the necessary command which aims to bring the variable to be controlled towards the sliding surface and then to its equilibrium point.

One of the essential assumptions in the design of systems with variable structure controlled by sliding modes, is that the control must switch between a value maximum $u+$ and a minimum value $u-$ as a function of the sign of the sliding surface. In this case, very high frequency oscillations called 'chatter' or 'Chattering' appear in sliding mode.

The structure of a sliding mode controller has two parts:

- A discontinuous command depending on the sign of the sliding surface u_n;
- A so-called equivalent command u_{eq} characterizing the dynamics of the system on the sliding surface.

$$u = u_{eq} + u_n \qquad \textit{Eq 5. 12}$$

We are interested in the calculation of the equivalent command and thereafter in the calculation of the attractive control of the system defined in the state space by the equation.

Equivalent control u_{eq}

The equivalent command u_{eq} is the nonlinear component that guarantees the attractiveness of the variable to be controlled towards the sliding surface. It can be interpreted as the average value the control takes when quickly switching between u^+ and u^-.

From the above equations we get to have:

$$\dot{S}(x) = \frac{dS}{dt} = \frac{\partial S}{\partial x}\frac{\partial x}{\partial t} = \frac{\partial S}{\partial x}(f(x,t) + g(x,t)u_{eq} + g(x,t)u_n) \qquad \textit{Eq 5. 13}$$

In sliding mode and steady state, the derivative of the surface is zero ($S(x)$=0 because the surface is equal to zero). This condition is used to determine the equivalent command:

$$u_{eq} = -\left(\frac{\partial S}{\partial x}g(x,t)\right)^{-1}\left(\frac{\partial S}{\partial x}f(x,t)\right), u_n = 0 \qquad \textit{Eq 5. 14}$$

During convergence mode, replacing the term u_{eq} by its value, we get a new expression for the derivative of the surface, that is:

$$\dot{S}(x) = \frac{\partial S}{\partial x} g(x,t) u_n \qquad \text{Eq 5. 15}$$

Discontinuous command u_n

The command u_n is the nonlinear component which makes it possible to guarantee the attractiveness of the variable to be controlled towards the sliding surface and to satisfy the convergence condition given by the previous equation $S(x)\dot{S}(x) < 0$, the problem comes down to finding $u_n$such that:

$$S(x)\dot{S}(x) = S(x)\frac{\partial S}{\partial x} g(x,t) u_n < 0 \qquad \text{Eq 5. 16}$$

The simplest solution verifying this condition is given by the sign function illustrated on the figure below:

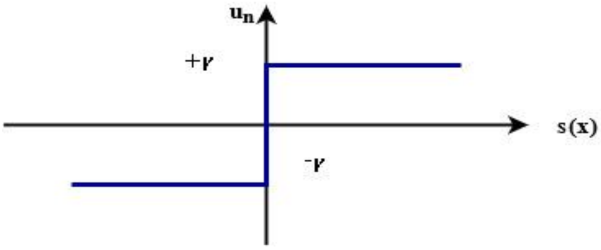

Figure 5. 8: Representation of the sign function

In this case, the command u_n is written as follows:

$$u_n = \gamma . \operatorname{sign}(S(x)) \qquad \text{Eq 5. 17}$$

By replacing the expressions, we obtain:

$$S(x)\dot{S}(x) = S(x)\frac{\partial S}{\partial x} g(x,t).\gamma.sign\big(S(x)\big) < 0 \qquad \text{Eq 5. 18}$$

In order to satisfy the attractiveness condition, the sign of the payoff γ must be opposite the sign of the factor $\frac{\partial S}{\partial x} g(x,t)$.

Chattering phenomenon

In sliding mode, the discontinuous command u_n switches between two values ($\pm\gamma$) at a theoretically infinite frequency. This is impossible to achieve in view of the presence of a delay time for the calculation of the command. Therefore, these high frequency oscillations occur, this phenomenon is called chattering phenomenon (Chattering or reluctance phenomenon).

Reluctance is the major drawback of the sliding mode control technique. Indeed, in this mode, the state trajectory no longer evolves exactly along the surface, but it tends to oscillate in its vicinity. This is detrimental to the proper functioning of the system, in particular for the power electronics elements.

The choice of the gain γ of the sign function is very influential and can minimize these oscillations:

- If γ is very small, the oscillations will be small but the response time will be long;
- If γ is very large, we will have a small response time but strong oscillations at the level of the control device which can damage the control device.

Reduction of the chattering phenomenon

Various methods have been developed in the literature to reduce the chattering. Since, the chattring problem is due to the discontinuous term (u_n) of the order, precisely the discontinuous function “($S(x)$)”, these methods are based on the replacement of this function by other continuous functions which approximate it as the saturation function and the smooth function.

Saturation function(sat)

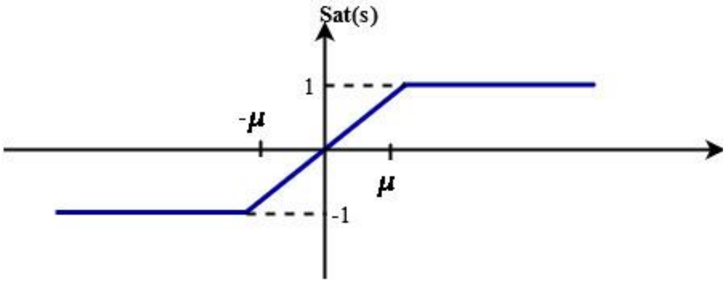

Figure 5. 9: Saturation function

The saturation function is given by:

$$\begin{cases} Sat(S) = 1 & \text{if} \quad S > \mu \\ Sat(S) = -1 & \text{if} \quad S < -\mu \\ Sat(S) = \dfrac{S}{\mu} & \text{if} \quad S|\mu| \end{cases} \qquad \text{Eq 5. 19}$$

Where μ is a small, positive parameter.

Smooth function

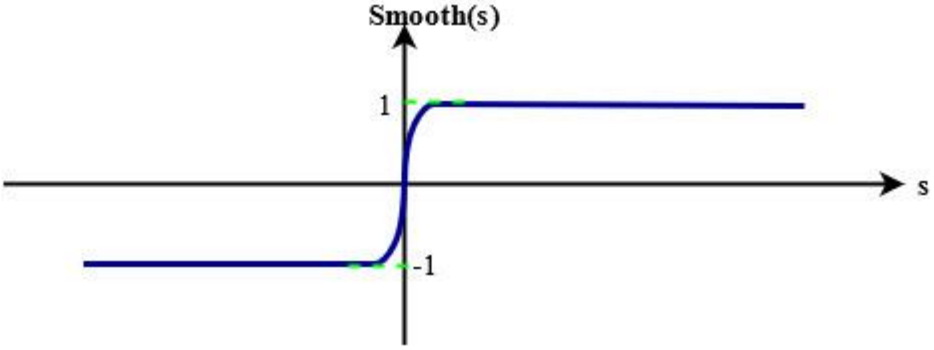

Figure 5. 10: Smooth function

The smooth function is given by:

$$Smooth\ (S) = \frac{S}{S + \mu} \qquad \text{Eq 5. 20}$$

5.8. MPPT control by sliding mode of the photovoltaic system

As with reference to the modeling of our boost converter, we applied the laws of Kirchhoff KCL and KVL to electric circuits characterised by two operating sequences of ON and OFF.

This time V_{Pv} is our V_{in} which serves as input voltage of our boost converter and V_s is our output voltage of the boost converter

Henceforth the equations controlling the boost converter as seen in figure 4.6 are given by:

$$\begin{cases} \dfrac{di_L}{dt} = -(1-D)\dfrac{V_s}{L} + \dfrac{V_{PV}}{L} \\ \dfrac{dV_{PV}}{dt} = (1-D)\dfrac{i_L}{C} - \dfrac{V_s}{RC} \end{cases} \qquad \text{Eq 5. 21}$$

If we suppose:

$X = [x_1 \ \ x_2]^T = [i_L \ \ V_s]^T$

$$\begin{cases} \dot{x}_1 = -(1-D)\frac{1}{L}x_2 + \frac{V_{PV}}{L} \\ \dot{x}_2 = (1-D)\frac{1}{C}x_1 - \frac{1}{RC}x_2 \end{cases} \qquad \text{Eq 5. 22}$$

Therefore, the expression $\dot{X} = AX + BU$ becomes:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -(1-D)\frac{1}{L} \\ (1-D)\frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{PV} \qquad \text{Eq 5. 23}$$

Choice of the sliding surface

As with reference to the previous chapter, the condition of the maximum power point MPP is given by:

$$\frac{dP_{PV}}{dV_{PV}} = 0 \qquad \text{Eq 5. 24}$$

The first step in the conception of control is to choose the sliding surface. Since the MPPT control aims to operate the photovoltaic system at its maximum power point, $s(x)$ is chosen as follows[15]:

$$s(x) = \frac{dP_{PV}}{dV_{PV}} = I_{PV} + \frac{dI_{PV}}{dV_{PV}}V_{PV} \qquad \text{Eq 5. 25}$$

With reference to the relation between the current I_{PV} and the voltage V_{PV} given in equation 3.25 we make some simplifying assumptions to make this expression useful, In the ideal case, R_s being negligible and R_p tends to infinity,

Therefore, the expression of the PV current becomes:

$$I_{PV} = N_P I_{Ph} - N_P I_{sat}\left(exp\left(\frac{V_{PV}}{nV_{th}}\right) - 1\right) \qquad \text{Eq 5. 26}$$

In a short-circuit,$V_{pv} = 0$ and $I_{pv} = N_p I_{cc}$,we replace this in the above equation (5.26), we get:

$$I_{cc} = I_{Ph} \qquad \text{Eq 5. 27}$$

With I_{cc} as the current of the short-circuit of the PV module.

If we suppose that $\exp\left(\frac{V_{PV}}{nV_{th}}\right) \gg 1$,we can write:

$$I_{PV} = N_P I_{cc}\left(exp\left(\frac{V_{PV}}{nV_{th}}\right)\right) \qquad \text{Eq 5. 28}$$

In an open-circuit,$I_{pv} = 0$ and $V_{PV} = N_s\, V_{co}$ .We replace this expression in the equation (5.28), we get:

$$I_{sat} = I_{cc}\left(exp\left(\frac{-N_s V_{c0}}{nV_{th}}\right)\right) \qquad \text{Eq 5. 29}$$

Thus, we obtain a new expression of current I_e.

$$I_{pv} = N_P I_{cc} - N_p I_{cc}\left(exp\left(\frac{V_{pv} - N_s V_{c0}}{nV_{th}}\right)\right) \qquad \text{Eq 5. 30}$$

Therefore, the derivative of current in comparison with voltage is given by:

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{N_p I_{cc}}{nV_{th}} exp\left(\frac{V_{pv} - N_s V_{c0}}{nV_{th}}\right) \qquad \text{Eq 5. 31}$$

We then substitute for the equation (5.29) we find:

$$s(x) = \frac{dP_{pv}}{dV_{pv}} = I_{pv} + \frac{dI_{pv}}{dV_{pv}} V_{pv} \qquad \text{Eq 5. 32}$$

$$s(x) = N_p I_{cc} - \left(N_p I_{cc} + \frac{N_P I_{cc}}{nV_{th}} V_{pv}\right)\left(exp\left(\frac{V_{pv} - N_s V_{c0}}{nV_{th}}\right)\right) \qquad \text{Eq 5. 33}$$

Determination of the equivalent control

To determine the condition of stability on the sliding surface, we make use of the notion of the equivalent control. Using the invariance conditions $\dot{s}(x) = 0$ .We calculate the expression for the equivalent control U_{eq} given by (2.8):

$$\dot{s}(x) = \frac{ds}{dt} = \frac{\partial s}{\partial x}\frac{dx}{dt} = \frac{\partial s}{\partial x_1}\dot{x}_1 + \frac{\partial s}{\partial x_2}\dot{x}_2 + \frac{\partial s}{\partial x_3}\dot{x}_3 \qquad \text{Eq 5. 34}$$

The expression (2.4) shows that $s(x)$ is in function of V_{pv} and not of i_L and V_s ,therefore we can write as follows:

$$\frac{\partial s}{\partial x_2} = \frac{\partial s}{\partial x_3} = 0 \qquad \text{Eq 5. 35}$$

and

$$\frac{\partial s}{\partial x_1} \neq 0 \qquad \text{Eq 5. 36}$$

$$\dot{s}(x) = \frac{\partial s}{\partial x_1}\dot{x}_1 = 0 \qquad \text{Eq 5. 37}$$

Where:

$$\frac{dx_1}{dt} = \frac{V_{pv} - x_2}{L} + \frac{x_2}{L}.U_{eq} \qquad \text{Eq 5. 38}$$

Therefore, the expression of the equivalent control is as follows:

$$U_{eq} = 1 - \frac{V_{pv}}{V_s} \qquad \text{Eq 5. 39}$$

Determination of the Discontinuous control

An explicit control approach needs to be formulated to bring the trajectory onto the sliding surface during convergence mode. This approach is called discontinuous control, with the law given by:

$$U_n = -\gamma sign\big(s(x)\big) \qquad \text{Eq 5. 40}$$

This approach of control of is called: control by sliding mode equivalent to constant rate.

Determination of the law of control

$$U = U_{eq} - \gamma.sign\big(s(x)\big) = 1 - \frac{V_{pv}}{V_s} - \gamma.sign\left(I_{pv} + \frac{dI_{pv}}{dV_{pv}}V_{pv}\right) \qquad \text{Eq 5. 41}$$

The advantage of this law is its simplicity. But, if gamma is too small, the reaching time will be too long. On the other hand, too large a gamma causes severe chattering. So, the choice of gamma is important. For the purpose of the simulation, the value of γ is chosen as 1000.This value gives us allows convergence of sliding mode without severe chattering and with a fast settling time.

5.9. Simulation

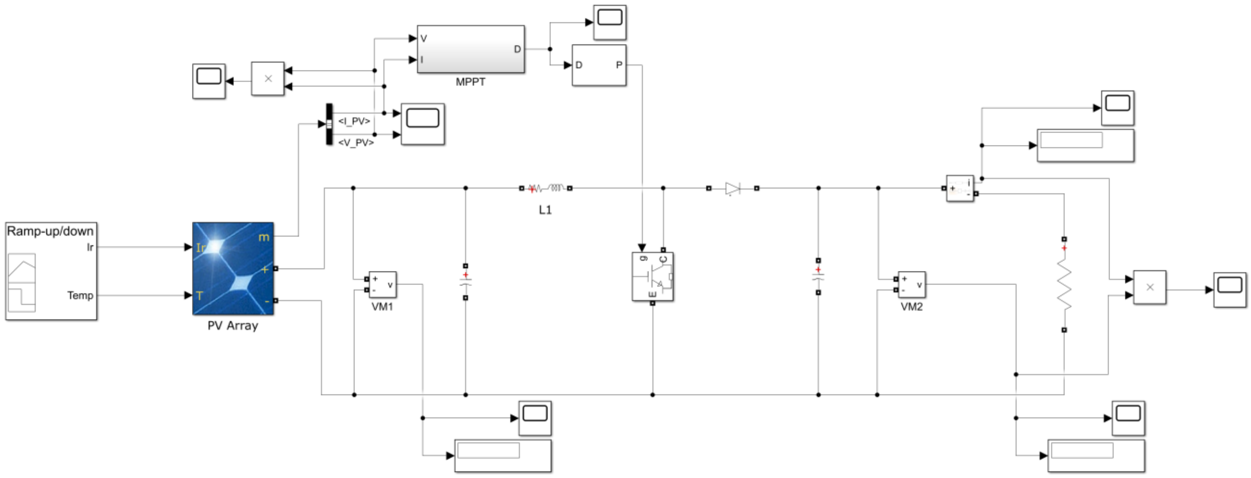

Figure 5. 11: Simulation of MPPT with boost converter

The diagram remains constant, all we need to change is the various MPPT techniques (P&O, INC COND and SM). After the simulation, we have obtained the following results:

5.10. Comparison of results

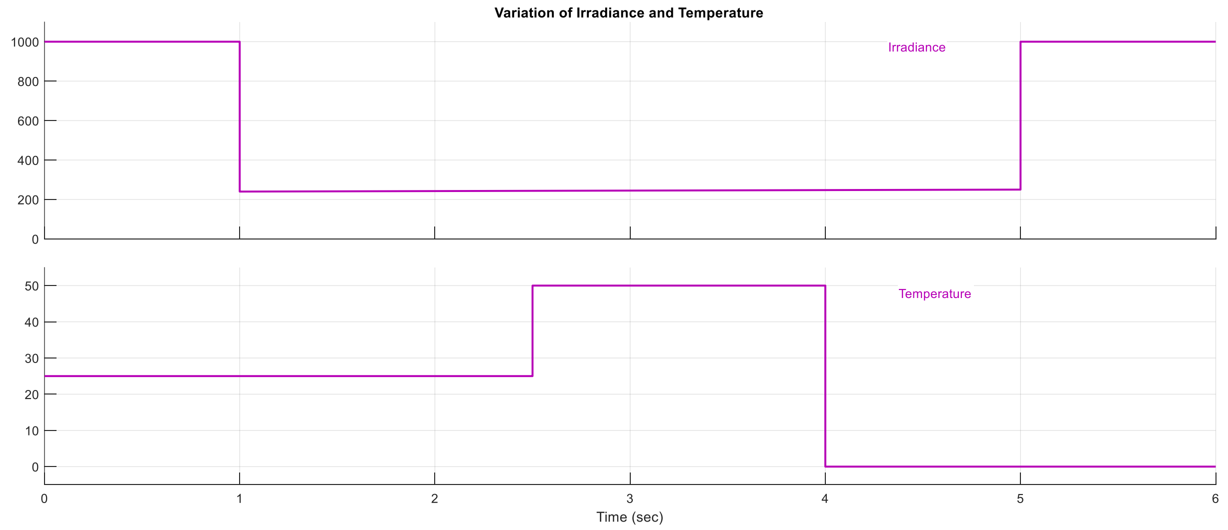

Figure 5. 12: Variation of irradiance and temperature for our simulation

We have nominal values of irradiation at 1000W/m^2 and temperature at 25°C from 0 to 1 seconds. This helps us to search for MPP at STC.

At exactly 1 seconds we have a decrease in irradiance from 1000W/m^2 to 250W/m^2, while temperature still remains constant at 25°C. This helps in simulating a case where we have low irradiance and nominal temperature. There is only a single change, we don’t have two changes simultaneously.

At 2.5 seconds we have a sharp increase in temperature to 50°C, while irradiation still remains constant at 250W/m^2. It remains like that till at 4 seconds where it goes down to 0°C. This simulates a case where we have high temperature and low irradiance

At 4 to 5 seconds, we have a case of low irradiance low temperature.

From 5 to 6 seconds, we have a high value of irradiance and low temperature.

Let’s keep these scenarios in mind as we look at the efficiency of our various MPPT for these varying atmospheric conditions.

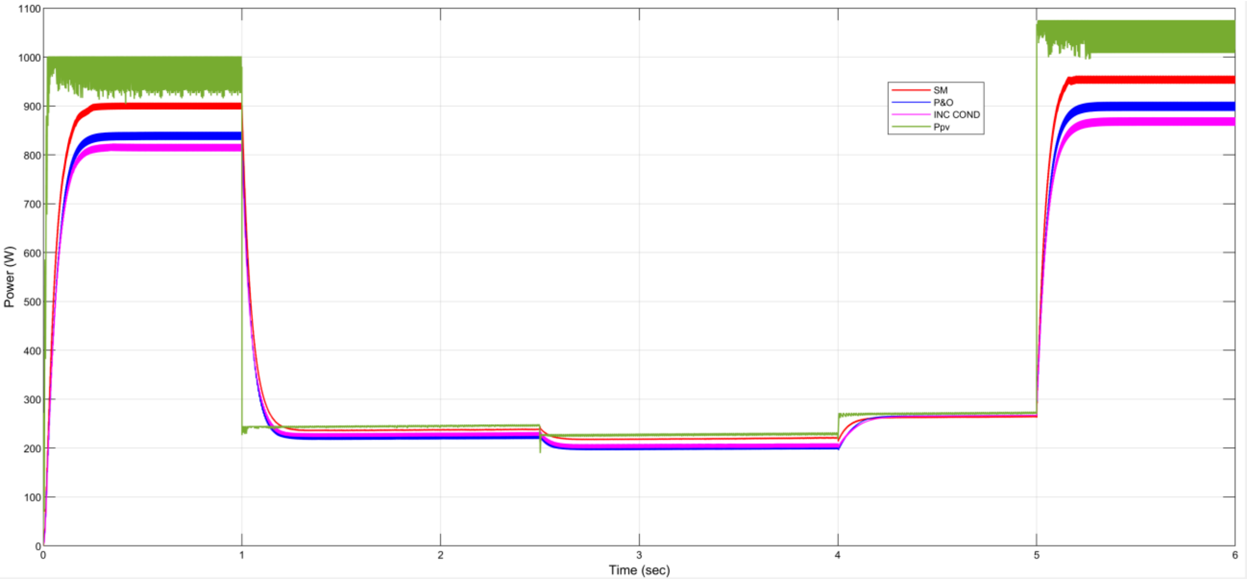

Figure 5. 13: Input power and output power from different MPPT

From the previous chapter, we already know that high irradiance and low temperature gives maximum value of power. Which has been further confirmed again in our simulation result

In green colour is the power coming from our PV module before being connected to our converter and load. It represents the maximum power possible from our PV panel. It gives us a visual representation of what to expect as output power.

We have different maximum power as different techniques converge towards a certain range of MPP. Sliding mode gave us the highest power in all scenarios and the most rapid response time, followed by P&O and lastly incremental conductance.

We notice a large drop in the value of power from the reduction of irradiance while change in temperature doesn’t have such a huge influence. This signifies that change in irradiance has a larger impact on the amount of power we can extract from a solar panel.

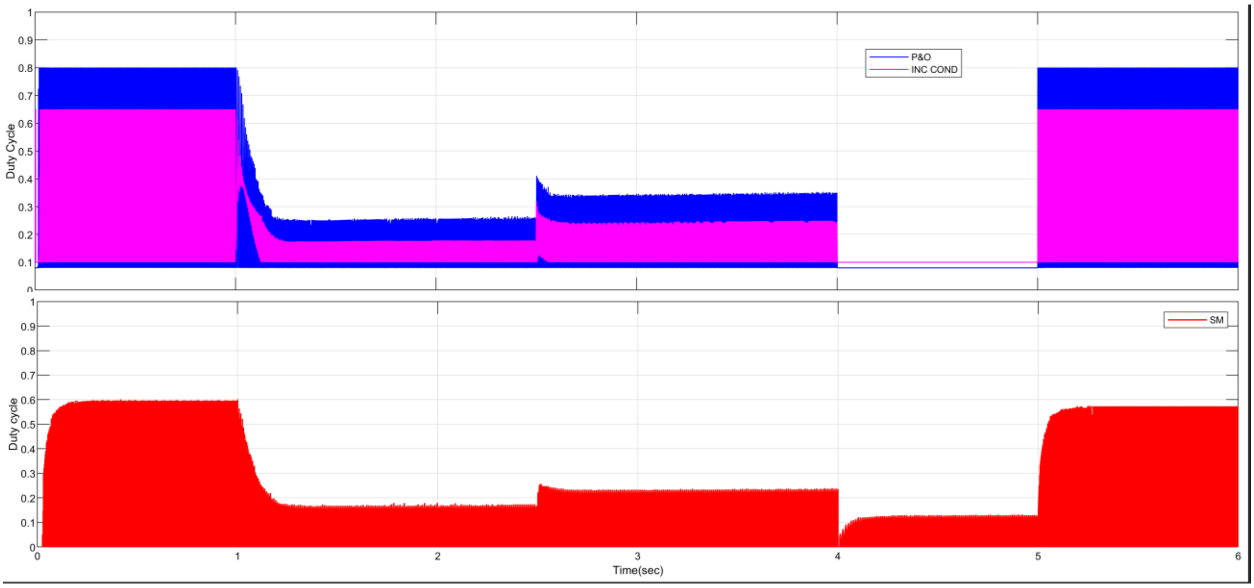

Figure 5. 14: Variation of duty cycle

From the figure above we notice that, a high value in power gives us a correspondingly high value of duty cycle and vice versa.

We observe that duty cycle of P&O varies the most, as it varied between the lowest value of 0.1 and its highest value of 0.8, followed by incremental conductance varying between 0.1 and 0.65

The duty cycle of SM has the best form amongst all three as it doesn't have a sharp decrease or increase for every change. But varies to have the possible best duty cycle for every time period. This in turn, allowed it to give us the higher MPP value we saw earlier compared to the other two.

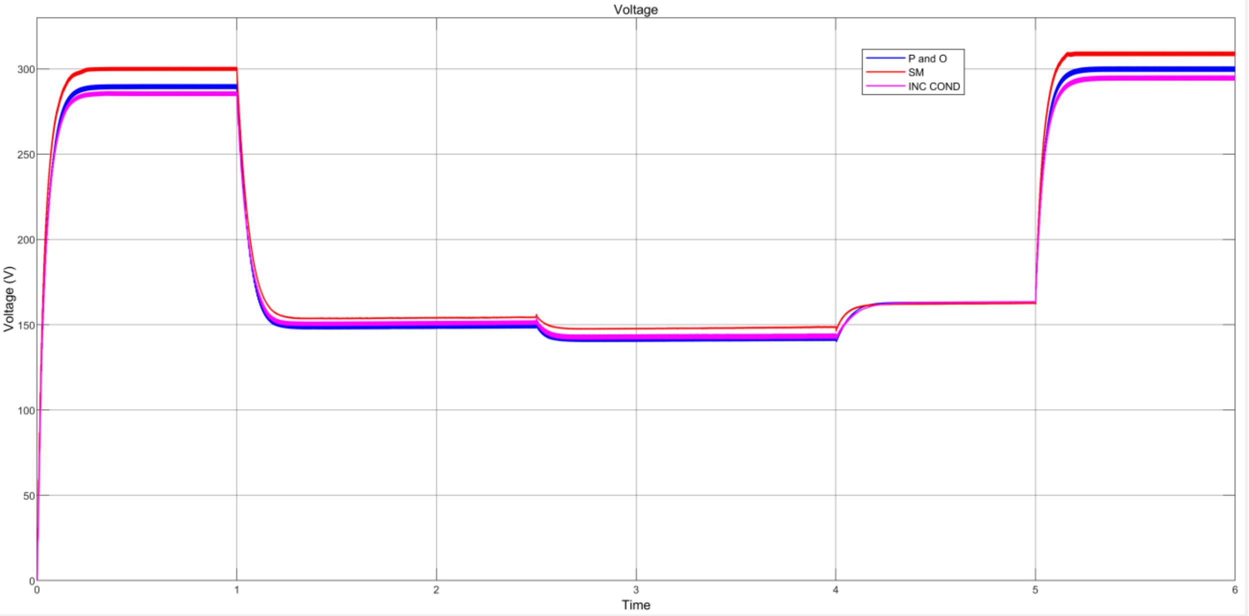

Figure 5. 15: Different output voltages of the 3 MPPTs

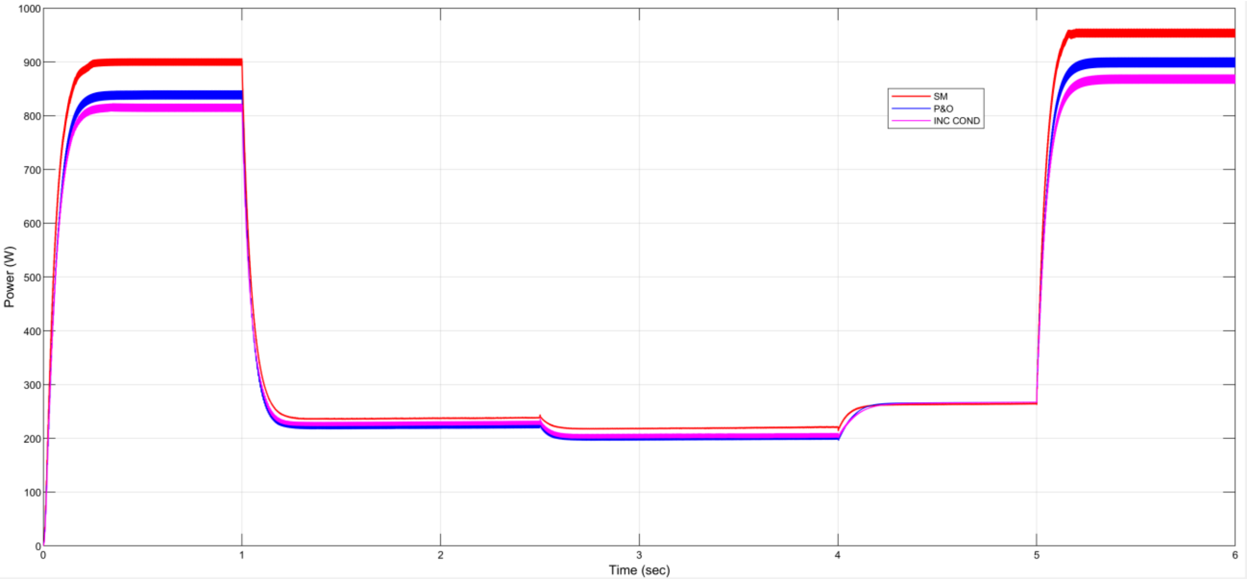

Figure 5. 16: Comparison of maximum power from different MPPT

The same explanation as that of figure 5.13 holds true. As it is still the same graphs but this time without the power from our PV panel.

The difference in power is because there isn’t a particular point on the PV curve, the 3 MPPTs tend towards this MPP, most of the time they give a value of MPP very close the peak of the curve. They give a value in a range around the peak of the curve (MPP) as seen in figure 5.16

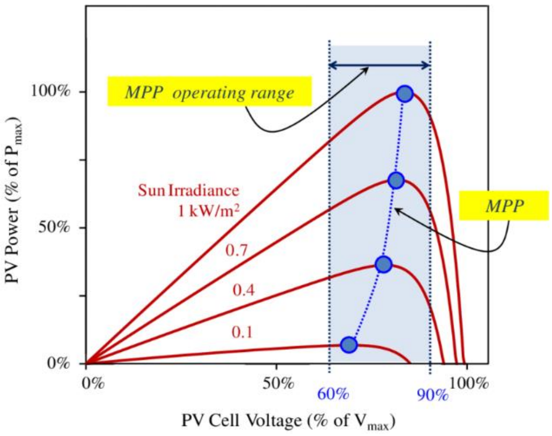

Figure 5. 17: MPP range

In conclusion, sliding mode control of MPPT is the best out of all the three we have tested in our simulation. Because, it gave us the highest value of power and also reaches setting time the quickest. This translates to a higher advantage in real life applications

5.11. Conclusion

Maximum Power Point Tracking (MPPT) is an electronic system which operates PV to gain a maximum power. MPPT is not a mechanical tracking however a MPPT can be used simultaneously with a mechanical tracking system. Maximum Power Point (MPP) does not lie at a particular point but it moves around P-V curve and it depends on light intensity and temperature.

By this simulation work, the PV system with Incremental conductance, P&O and Sliding Mode MPPT algorithm has been successfully implemented in the MATLAB/Simulink. Our MPPT forces the PV module to operate at close to maximum power operation point in order to draw maximum available power. The results of the output converter power shows that it is achieving the maximum extracting power and it is constantly working near the maximum operating point of the PV module. Out of all the three algorithms tested, sliding mode has proven to be the best

CHAPTER 6

COMPARATIVE ANALYSIS OF MPPT OF GRID CONNCECTED PV SYSTEMS

6.1. Introduction

A grid-connected photovoltaic system, or grid-connected PV system is an electricity generating solar PV power system that is connected to the utility grid. Grid-connected photovoltaic systems are designed to operate in parallel with the electric utility grid Grid-connected PV systems are typically designed in a range of capacities from a few hundred watts from a single module, to tens of megawatts from a large ground mounted system. This presents the electricity companies with a range of connection requirements depending on where they connect to the electricity network and at which voltage level.[27]

While the main components of a grid-connected PV system may differ in detail between system sizes the overall concepts are the same. A typical domestic grid-connected PV system as shown in figure 6.1

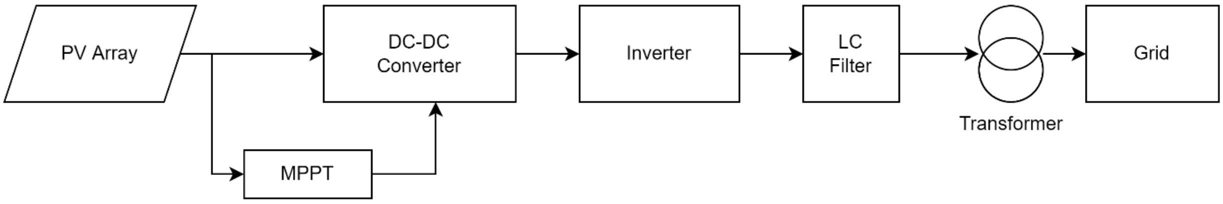

Figure 6. 1:A typical grid connected PV system

For the purpose of simulation, our grid-connected PV system consists of:

- The PV modules themselves,
- Boost converter,
- MPPT controller which controls our boost DC-DC converter,
- 3 level bridge inverter and,
- Our utility grid itself

In grid-connected applications, the power is directly supplied to the grid – and the photovoltaic modules and inverters are the important blocks. This decreases the overall price of the plant and also reduces the necessary maintenance required, as the most maintenance-demanding parts are the batteries.

The PV inverters for grid connected systems can be of different topology and operation than off-grid ones. They have to produce excellent quality sine wave outputs with low ripples i.e., less THD, they have to match the frequency and voltage of the grid for synchronisation purpose – and extract maximum power from the PV modules this is done through the use of MPPT algorithms.

The inverter input finds from I–V curve of the photovoltaic string cell until the maximum power point is achieved.

- The PV grid inverter always controls the grid and output voltage and frequency. The Pulse Width Modulation is the most effective modulation technique, it can function at various frequency ranging from 2 to 20 KHz.
- Grid connected inverters are classified as Voltage Source Inverters (VSIs) and Current Source Inverters (CSIs), VSI inverters are used in PV applications. The complete diagram of PV panels and VSI with grid integration is provided in Figure 6.1

6.2. Inverters

Inverters are a very important part or component of the photovoltaic system, most household devices and appliances if not all operate on alternating current, therefore, it is necessary to ensure that the current flowing through is of the same nature (AC). And in a case like ours, where the PV system is connected to a grid, an inverter is also needed.

As seen in the above chapters, a PV generates a direct current, therefore, it is important to bring in a converter that converts the direct current to alternating current as that is the purpose of the Inverter. In this section, we are going to look at the operating principles, and analysis of grid-connected inverters, in particular, three-phase inverters.

6.2.1. Structures of Photovoltaic Inverters

Photovoltaic inverters are very in the photovoltaic power system applications. Inverters are generally divided into AC-DC converters (changes alternating current to direct current), and DC-AC converters (changes direct current to alternating current and generate arbitrary frequencies and Voltages).

Topologies surrounding inverters end on the characteristic fluctuations, therefore a suitable inverter should always be chosen by a solar PV plant designer for an accurate application. PV inverters are classified into three main types i.e., current source inverters (CSI), impedance source inverters (ISI), and voltage source inverters (VSI). VSIs are most commonly used because they behave naturally as voltage sources, as required for many industrial applications.

6.2.2. Voltage source type inverters

This gives reference to how the output voltage of the voltage source inverters is controlled. A large value capacitor is in parallel across the DC input line of the inverter and the inverter acts as a voltage source. The output of the converter must-have characteristics of a power supply. Series reactors are required for each phase in the case of low-impedance loads. The voltage can be adjusted directly by a voltage source inverter and the voltage-driven across a load can be adjusted by varying the drive number. With this type of inverter, the blocking diodes do not need to be reversed, resulting in higher output efficiency than current-source inverters and lower voltage losses.[70]

6.2.3. Current source type inverters

Current source inverters are controlled by the output current. A large value inductor is placed on the input DC line of the series inverter. In addition, the inverter acts as a power supply. The inverter output must have the properties of a voltage source. In motor applications, capacitors are required between each phase of the motor input. All household appliances and artificial power operations are typically employed with a current source inverter; however, voltage source inverters are easier to control than the current source type. Likewise, the HVDC power transmission has used a current source inverter. Further, a long-distance power sale is commensurable to a DC current before an AC conversion and a DC current is bestowed through a large reactor.

6.2.4. Impedance source type inverters

There are different topologies for single-phase ISI namely "Z", "qZ" and "TZ" inverters. The converter consists of capacitors and inductors, switches, and diodes. The capacitors and inductors are arranged to form an input impedance for the inverter. An applied DCAC conversion system and booster parts are used with the bridge technology of the latest Z-source inverters (ZSI or ISI). ZSI brings an additional benefit to a normal single-level converter topology because the (ST) trigger does not allow the inverter to self-destruct for a long time. The problems that have arisen are eliminated. For natural VSI and CSI inverters, a unique impedance network is applied in buck and buck modes.

6.2.5. Voltage Source Three-Phase Inverter

The three-phase voltage source inverter consists within three half-bridge switches used to generate a sinusoidal voltage waveform for each phase. The figure below shows the power bridge of the three-phase two level voltage source inverter.[71]

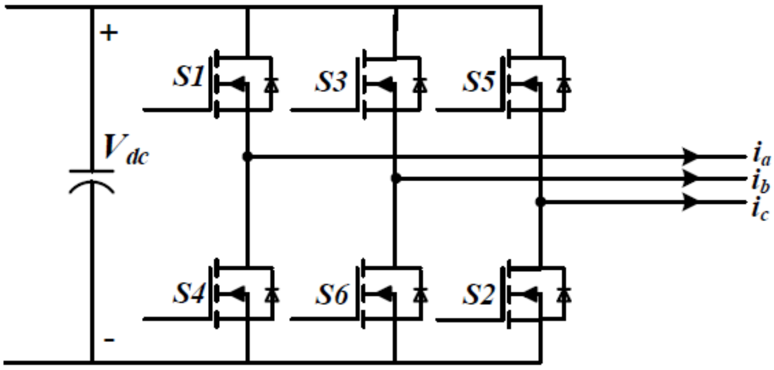

Figure 6. 2: Circuit representation of a three-phase two level voltage source inverter

When each half-bridge is switched according to the selected PWM method, the unfiltered output of the power bridge is generated as a pulse-width modulated voltage waveform. A filter is required to generate a sinusoidal voltage curve and to be able to feed power into the grid in a controlled manner. The single-line chart with an LCL filter is shown in the figure below.

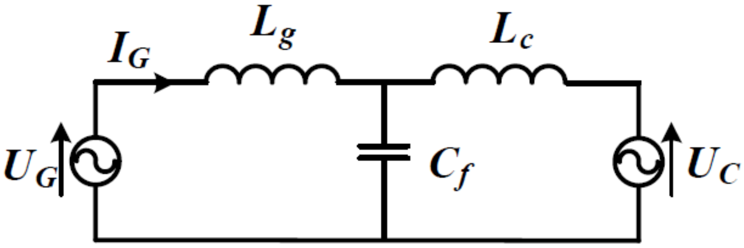

Figure 6. 3: Simplified single-line diagram of a three-phase inverter

In order to transfer power to the grid in a stable way, line impedance is required since power transfer is done by changing the g phase and magnitude difference between the inverter output voltage and grid voltage. In order that this line impedance limits the current flowing from the m inverter ta o grid or vice versa. Consistent with the signal line diagram of the inverter phasor diagram three-phase voltage source inverter for the different operating conditions is given in the figure below:

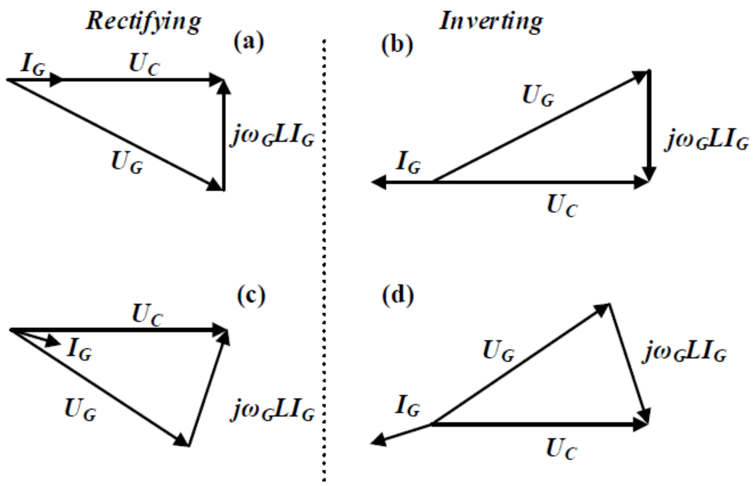

Figure 6. 4: Phasor diagram consistent with operation mode of inverter (a) Unity power factor rectifying, (b) Unity power factor inverting, (c) Non-unity power factor rectifying, and (d) Non-unity power factor inverting

As can be seen in the figure above, UC defines the inverter output voltage while UG defines grid voltage. Inverter output line current is defined by the voltage and phase difference between inverter output and grid, also the road impedance between inverter output and grid. Since UC value is controllable with the change of switching state, to regulate the line current, the system modifies inverter output voltage. Besides, line impedance is important for the control loop to work in a stable way and to control line current. If the filter impedance is, just too small excessive current flows can occur, whether or not there is a minor phase and voltage difference between inverter output and grid. When the phasor diagrams are examined, it is often seen that in inverting mode inverter output voltage waveform is leading compared to the rid voltage waveform. In addition, reactive power flow mostly occurs thanks to the magnitude difference between the inverter output voltage and grid voltage. During this phasor diagram, the resistance between inverter output and the grid is ignored and it is often included when the filter resistance should be taken into consideration.

6.3. Control strategy for Three-Phase Inverter

The most important and basic requirement for grid-connected inverters is to keep inverters synchronized with the grid so that, the inverter is often connected to the grid. The inverter can feed the correct quantity of power to the grid even when the grid voltage changes its frequency, phase, and, variation amplitude. As mentioned, there should be an impact system to ensure the high quality of the power defined by stored or injected power. Likewise, the harmonics for the nonlinear load drawn from the grid and therefore the phase difference between voltage and current of a network need to be compensated by capacitor and inductor as the loads. The output current, grid current, load current, or any node current could also be controlled and the control system is focused on such as harmonic detection, power control, and power factor correction. In addition, the grid voltage phase should be inserted into the system and applied by a phase-locked loop. One of the most important tasks of the control system performed on the grid-connected inverter, especially, the parameters of voltage, current, and power are often controlled and one or a number of these parameters depend on the requested demand made by a control system.

6.4. Grid

The electrical grid is the electrical power system network comprising of the generating plant, the transmission lines, the substation, transformers, the distribution lines and also the consumer.

Electricity generation facilities generally have been developed in locations far from consumers, electric grid acts as a liaison between the two.

The three main components of the grid are explained below

- **GENERATION** – There are mainly two types of generation – centralized and decentralized. Centralized generation refers to large-scale generation far from consumption. This includes coal, nuclear, natural gas, hydro, wind farms and large solar arrays. The grid connects centralized power to consumers. Decentralized generation occurs close to consumption, for example rooftop solar.
- **TRANSMISSION and DISTRIBUTION-** Transmission includes transformers, substations and power lines that transport electricity from where it is generated to consumers. When electricity is at high voltages, transmission losses are minimized over long distances and resistive transmission lines. Therefore, at the point of generation, substations contain transformers that step-up the voltage of electricity so that it can be transmitted. Transmission is achieved via power lines and can occur either overhead or underground. When it arrives at points of consumption, another substation is found to step-down the voltage for end-use consumption[3].
- **CONSUMPTION** – There are various types of consumers; namely industrial, commercial and residential consumers. Each of these consumers has different needs but in general electricity delivers important energy services like light and power for appliances.

6.5. Grid connected PV MPPT

6.5.1. Simulation

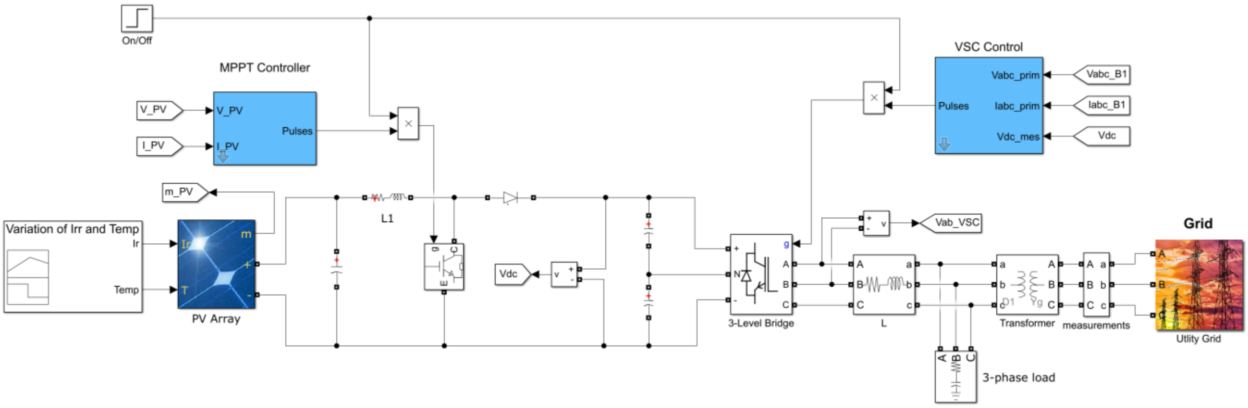

Figure 6. 5: Grid connected PV array

Figure 6.4 above gives us the global diagram of a grid connected PV system. We have an array of PV modules connected in series and parallel in such a way that at nominal value of irradiance of 1000W/m^2 and nominal temperature of 25℃ our array generates a combined power of 100KW.

We used the same variation of irradiance and temperature as in the previous chapter

Our MPPT was switched on at 0.05 seconds, to allow for our duty cycle and MPPT algorithm to reach settling state.

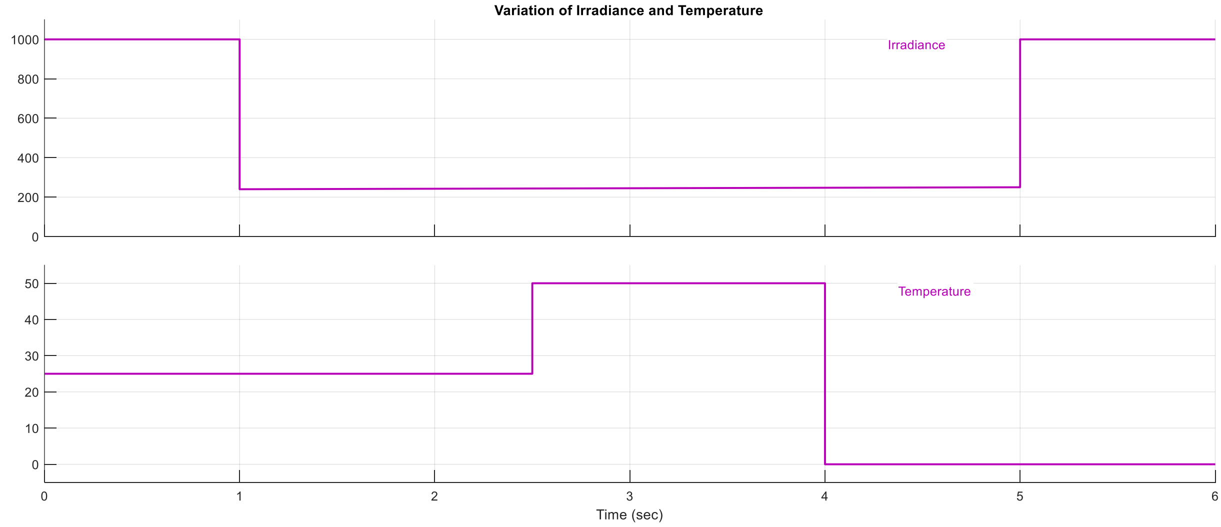

Figure 6. 6: Variation of irradiance and temperature

For these variations in irradiance and temperature, we have obtained the following results

6.5.2. Results

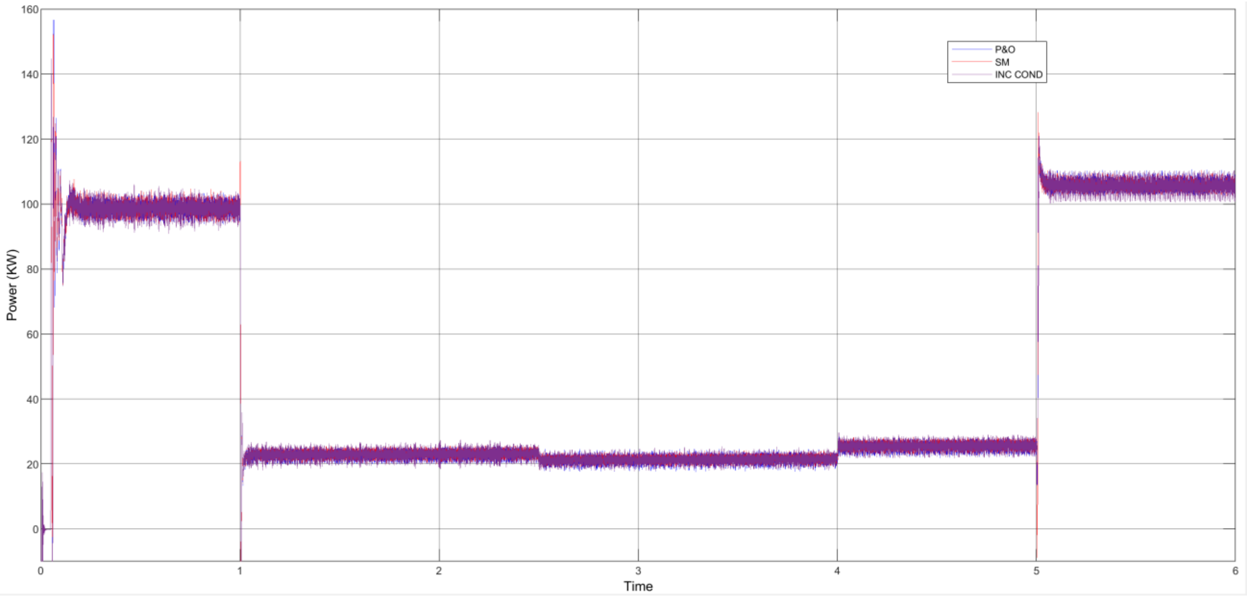

Figure 6. 7: Tracked MPP for all three MPPT

There is no noticeable difference in the MPP tracked by the 3 MPPT techniques. As they have all given very close values of power. This is due to the very high value of voltage and power we are working with. We observe a rapid oscillation at the time of activation of our MPPT but we quickly achieve steady state.

We notice some sort of drift in power for change in irradiance, overall, it doesn’t have much effect.

We have attached the graphs of power for each MPPT separately below

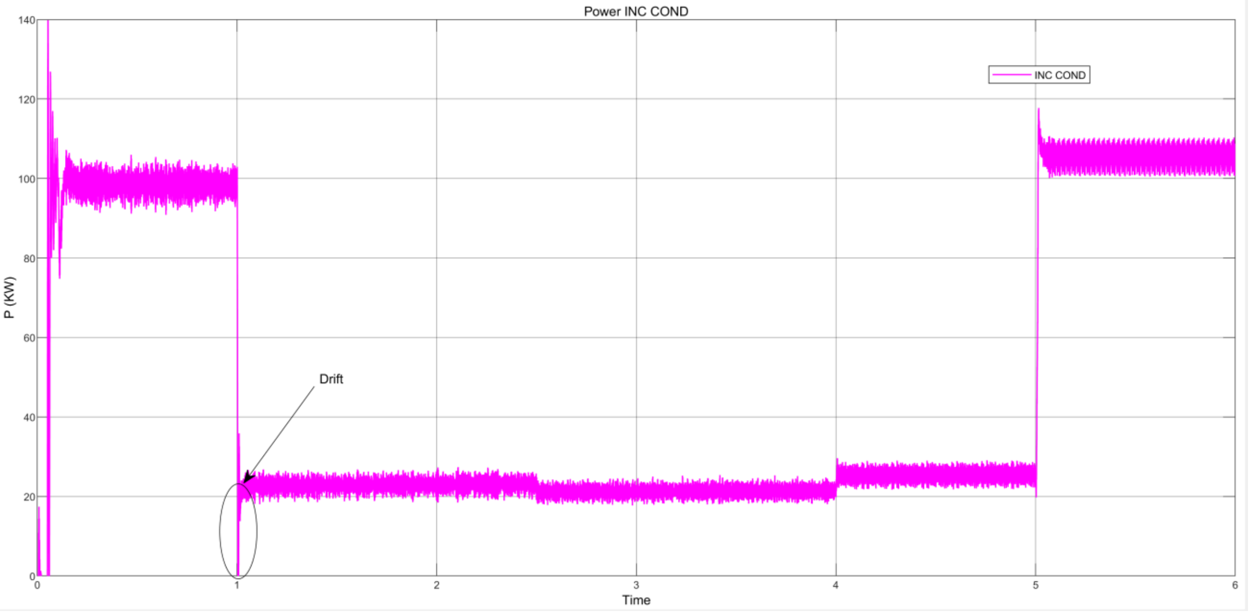

Figure 6. 8: Tracked power-incremental conductance

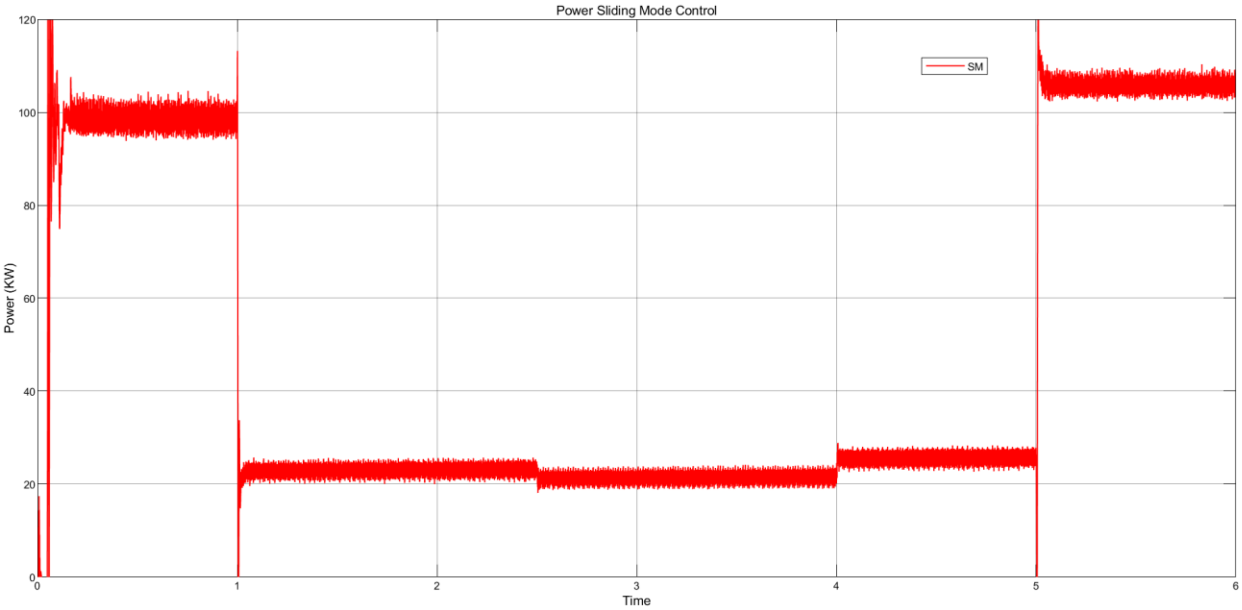

Figure 6. 9: Tracked power - sliding mode

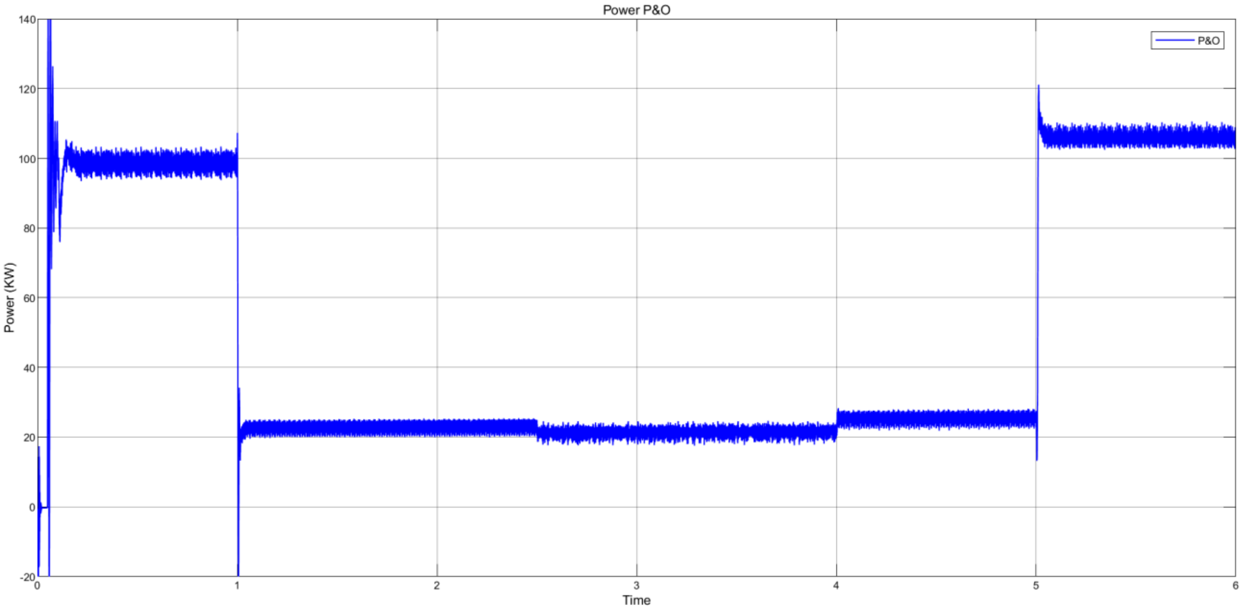

Figure 6. 10: tracked power - P&O

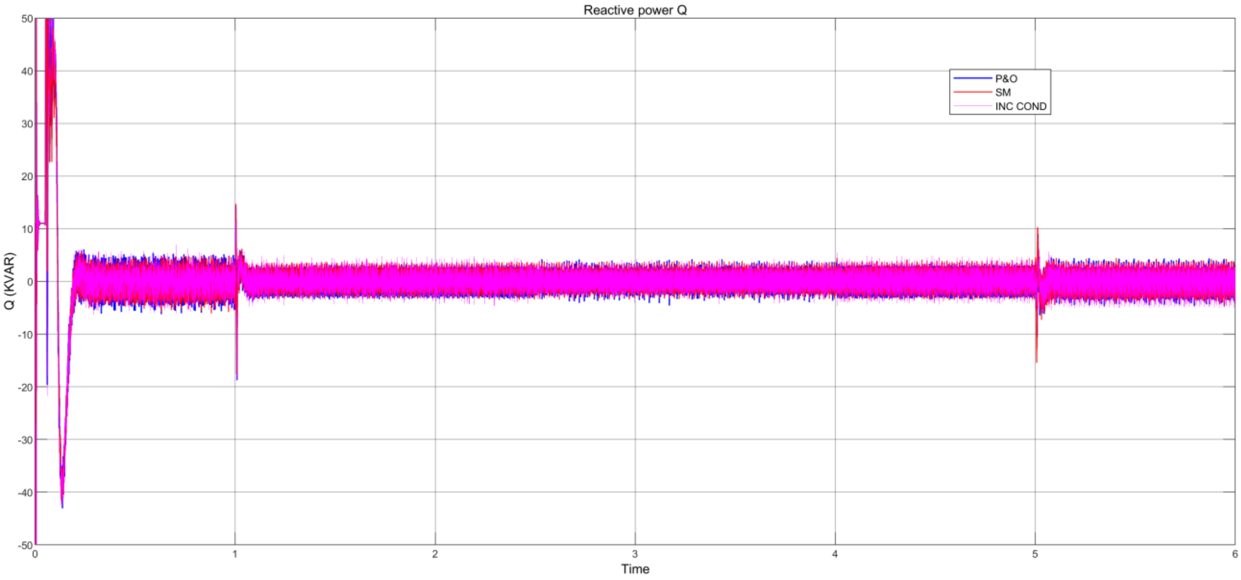

Figure 6. 11: Reactive power for all three MPPT

For the reactive power from the grid, it is zero except for a slight oscillation when there was change in radiation, and then it goes back to zero.

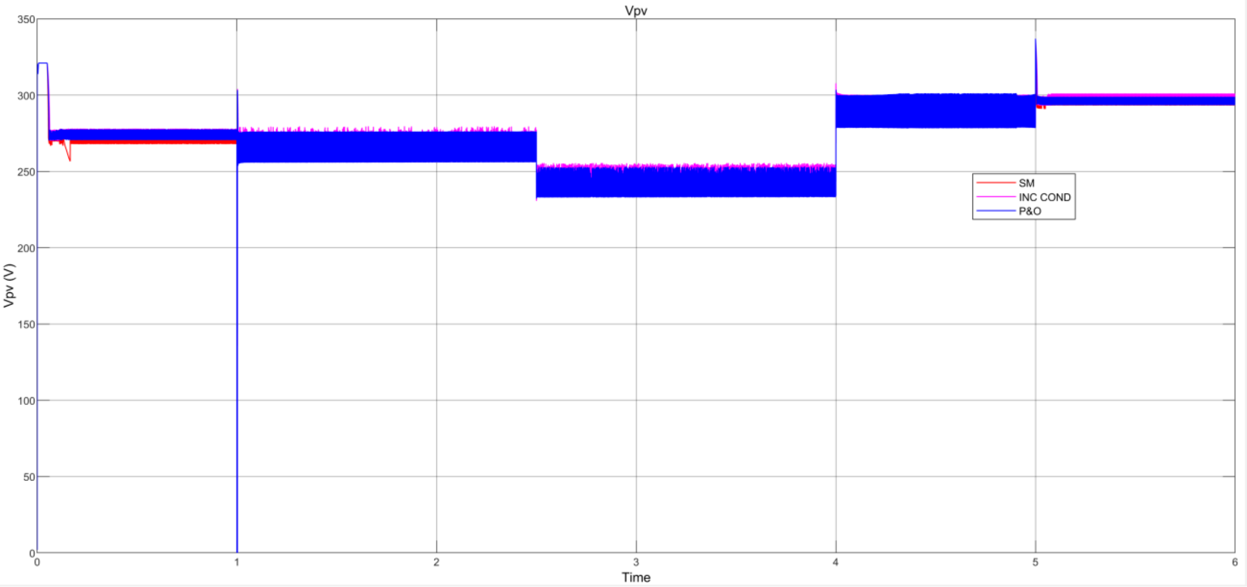

Figure 6. 12: Vpv for all three MPPT

The figure above shows the voltage coming from our PV array for all three MPPT. its values for three MPPT techniques remain largely the same. Change in temperature at 2.5 and 4 seconds has a more noticeable effect on the output voltage of our array compared to change in irradiance at 2 seconds and 5 seconds

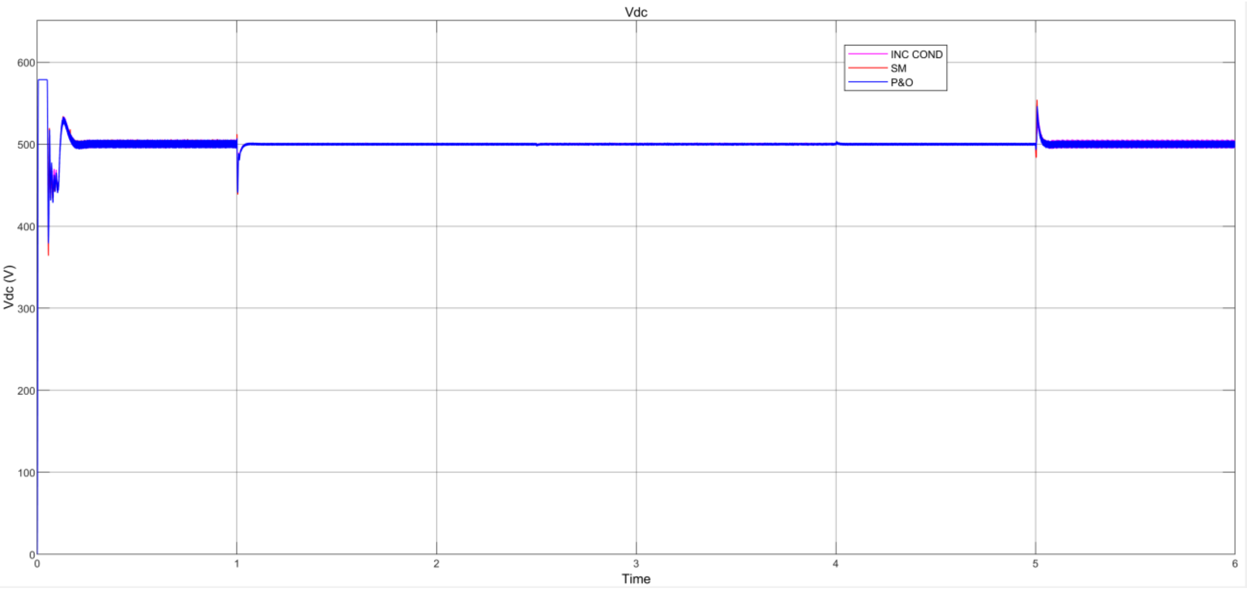

Figure 6. 13; Vdc - all three MPPT

Vdc is the voltage coming from our boost converter, which we then connect to our inverter. we have modelled our converter to give a constant output of 500V. There is no difference in Vdc for all three techniques.

Phase voltages and current, and line voltages and currents; for all three techniques are the same. For the sake of avoiding congestion in graphic visualisation. We have chosen to take the graphs from a single technique (SM)

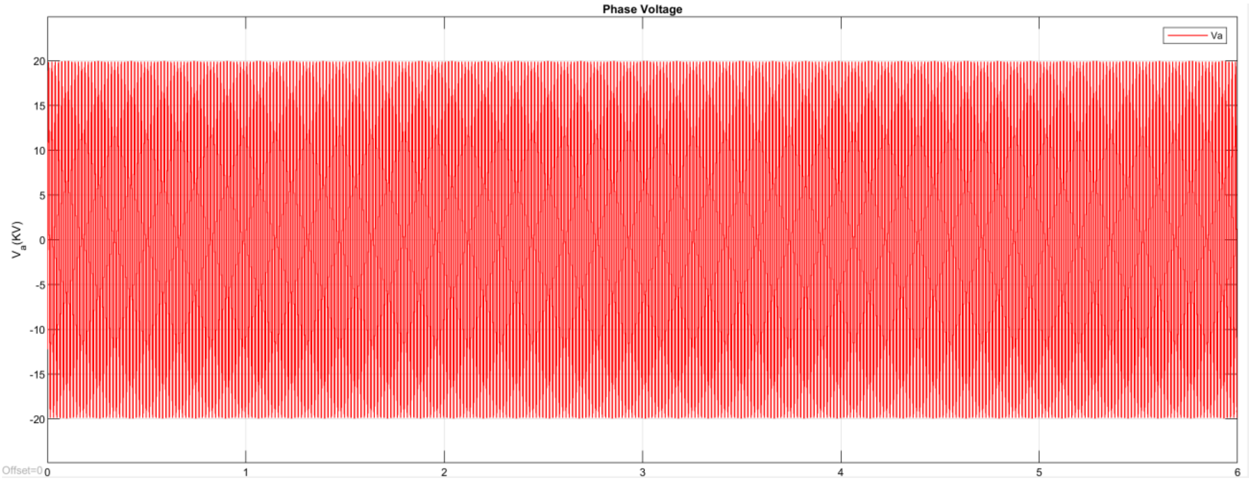

Figure 6. 14: Grid phase voltage

Phase voltage remains constant at 20KV, not affected by change in irradiance and temperature

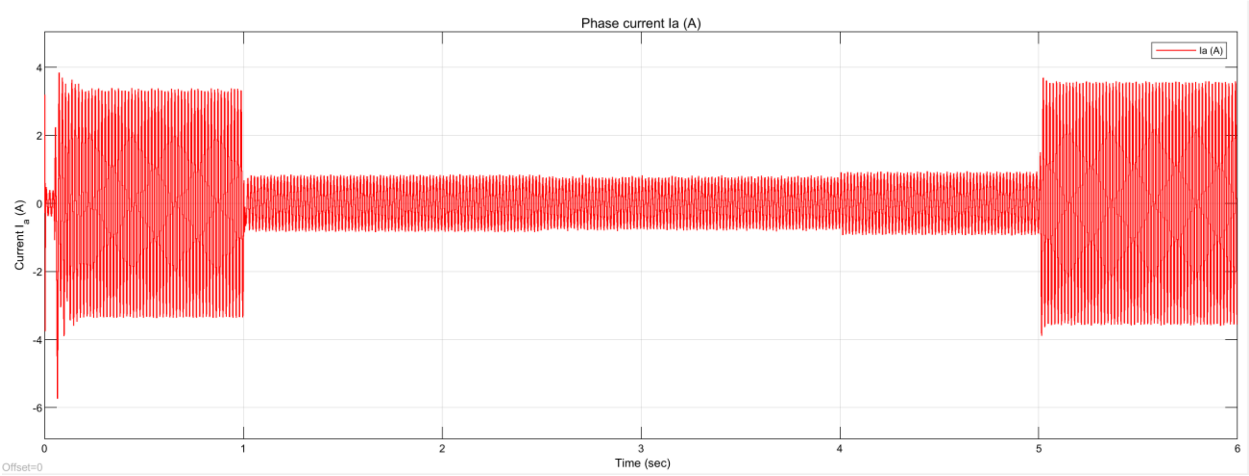

Figure 6. 15: Phase current

Current is relatively null compared to voltage, at high irradiance current is high and low at low irradiance. Change in temperature has no noticeable influence. Same holds true for both phase and line current

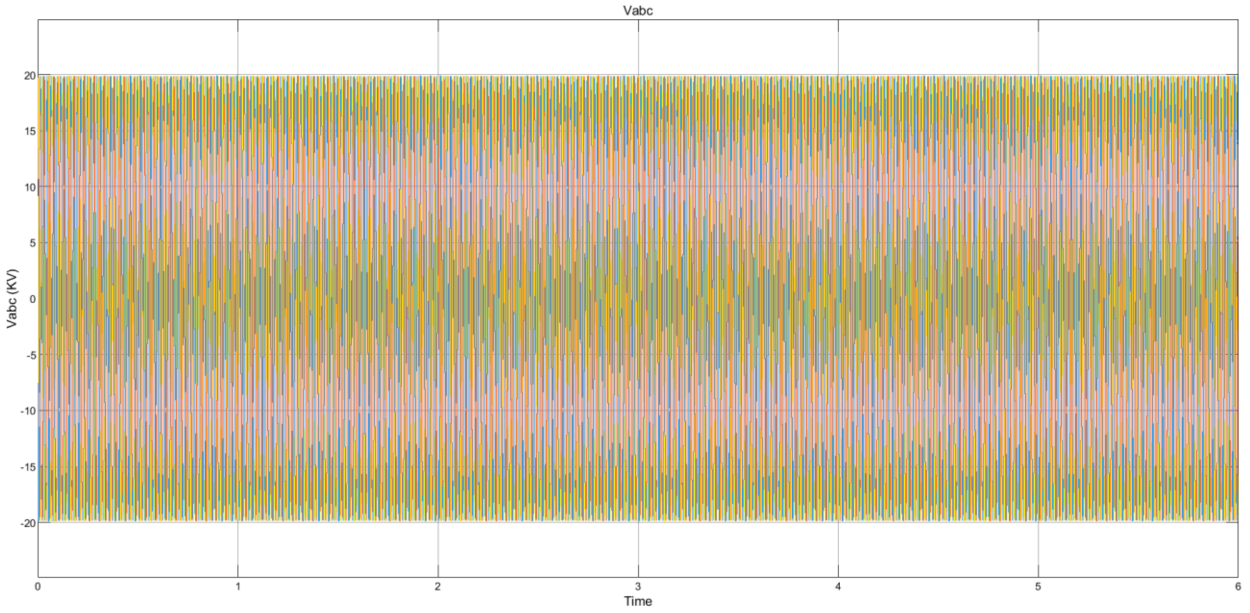

Figure 6. 16: Vabc of grid

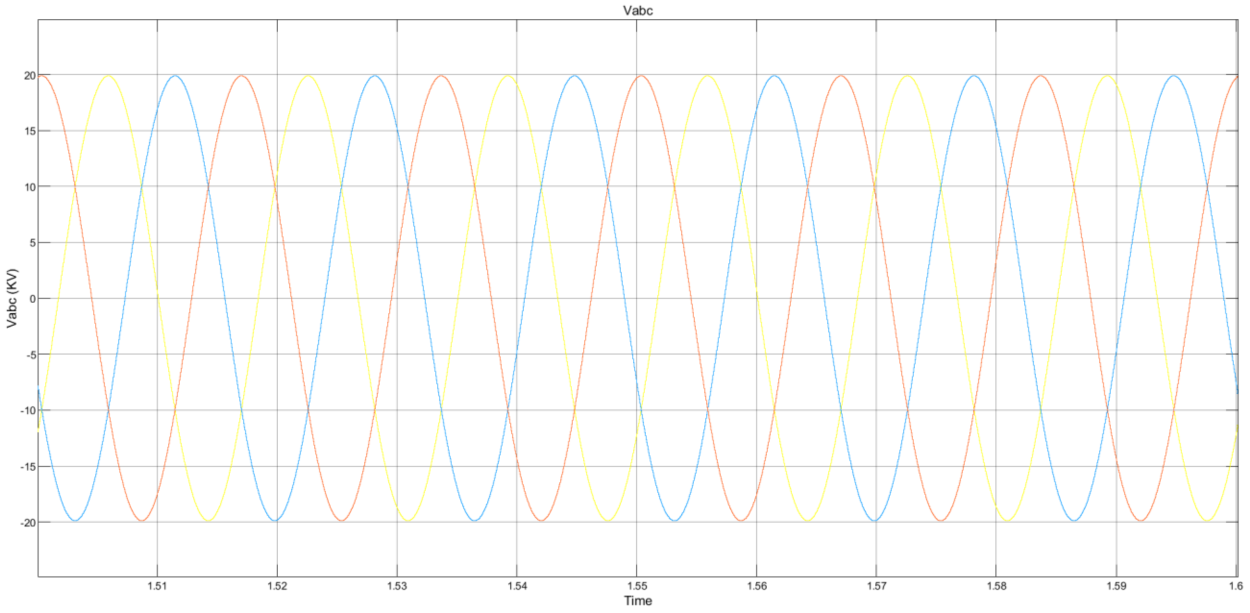

Figure 6. 17: Vabc of grid - zoomed in

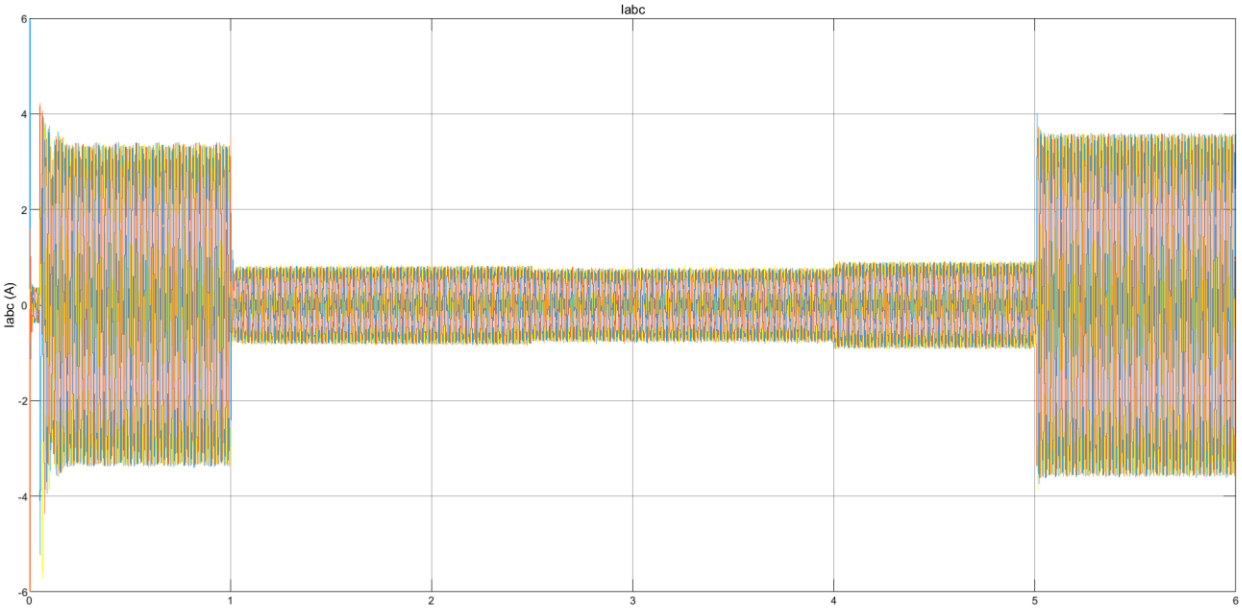

Figure 6. 18: Iabc of grid

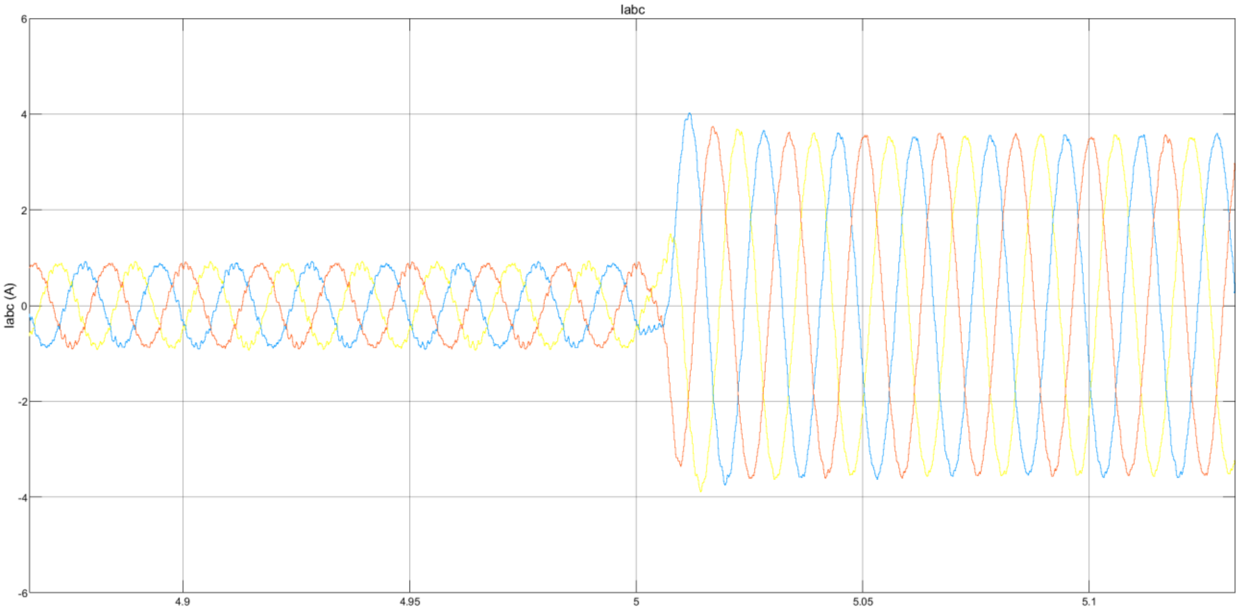

Figure 6. 19: Iabc of grid - zoomed in

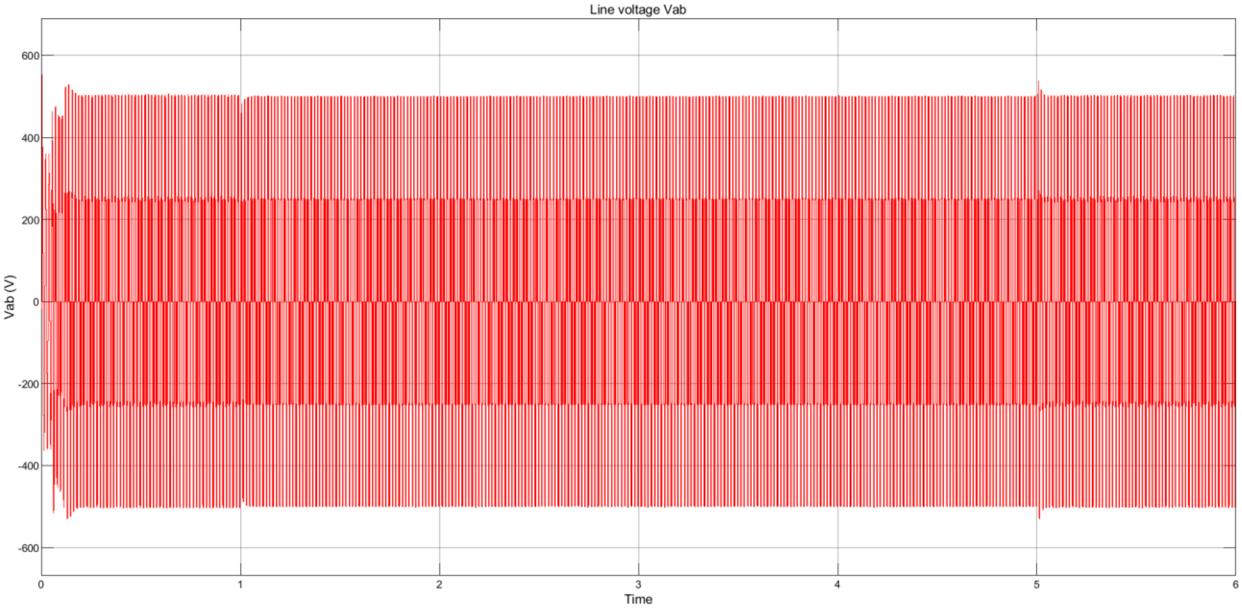

Figure 6. 20: Line voltage Vab from our inverter

For the linkage between our inverter and grid; since we know the amplitude and frequency at which our grid operates, we can avoid the use of PLL (Phase Locked Loop), because our frequency does not vary, causing us to have an open loop control.

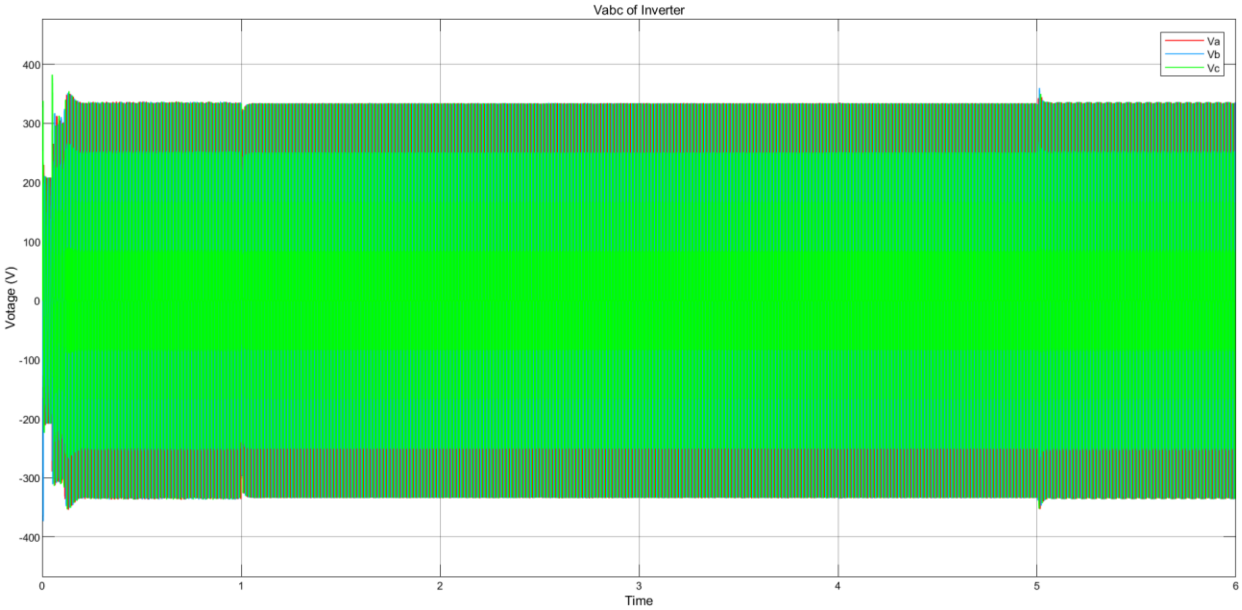

Figure 6. 21: Vabc of Inverter

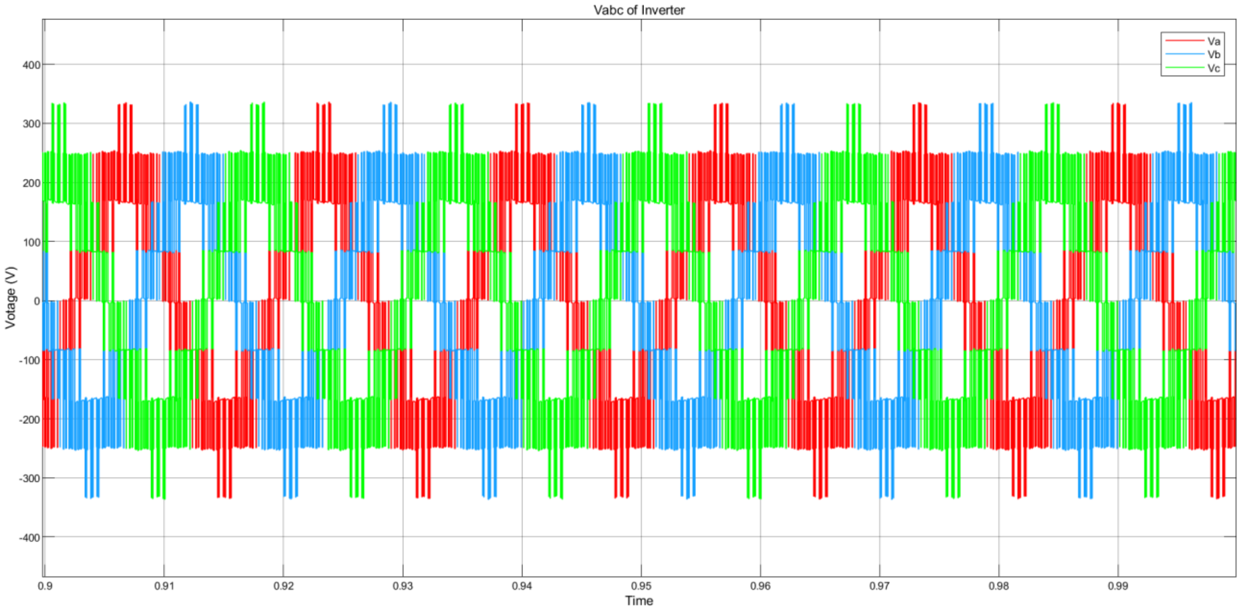

Figure 6. 22: Vabc of inverter –zoomed in

Change in irradiance or voltage has no effect on voltage, it remained constant. Voltage from our inverter has an almost sinusoidal waveform but not perfect. Because the opening and closing of gates in switches in inverter and its control by PWM affects mainly the voltage

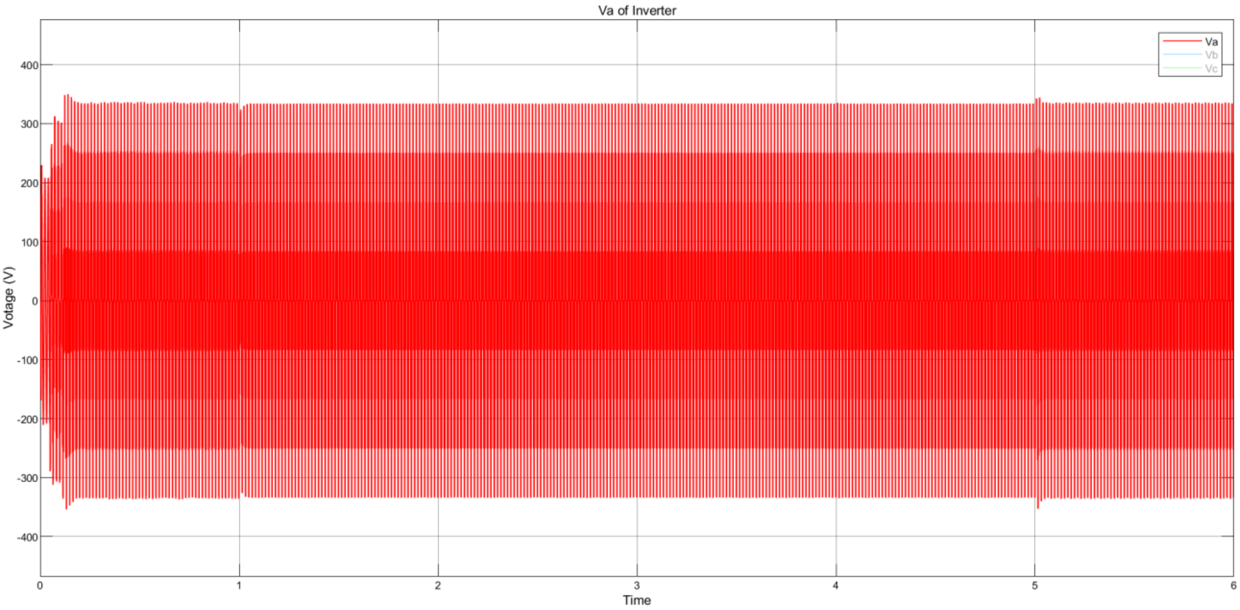

Figure 6. 23: Va of inverter

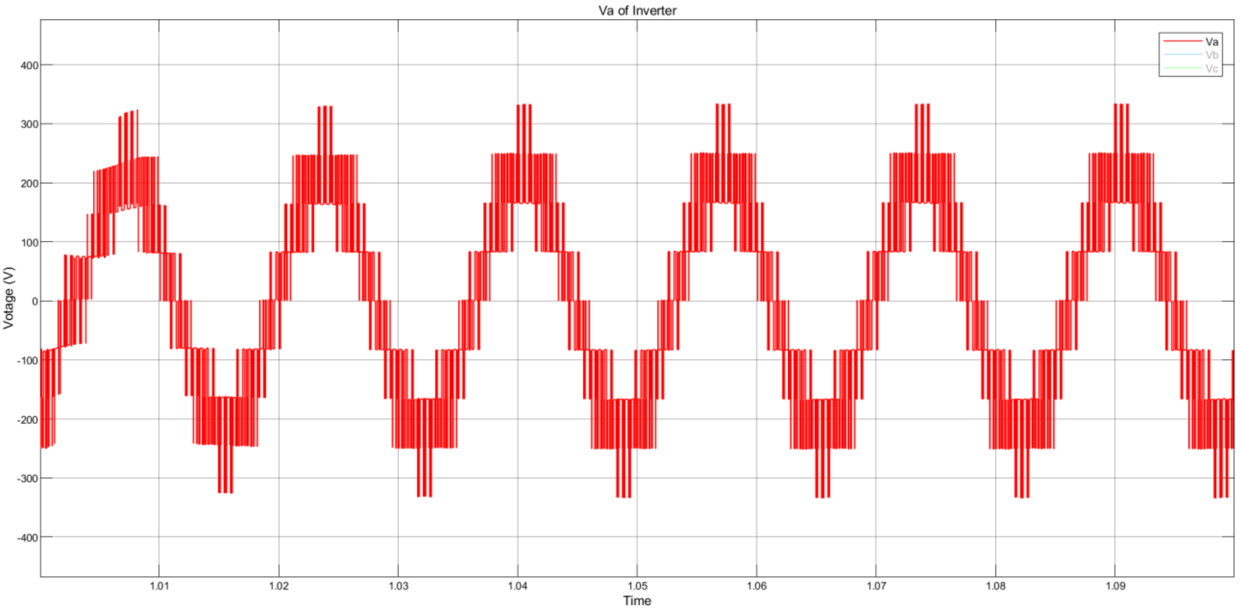

Figure 6. 24: Va of inverter –zoomed in

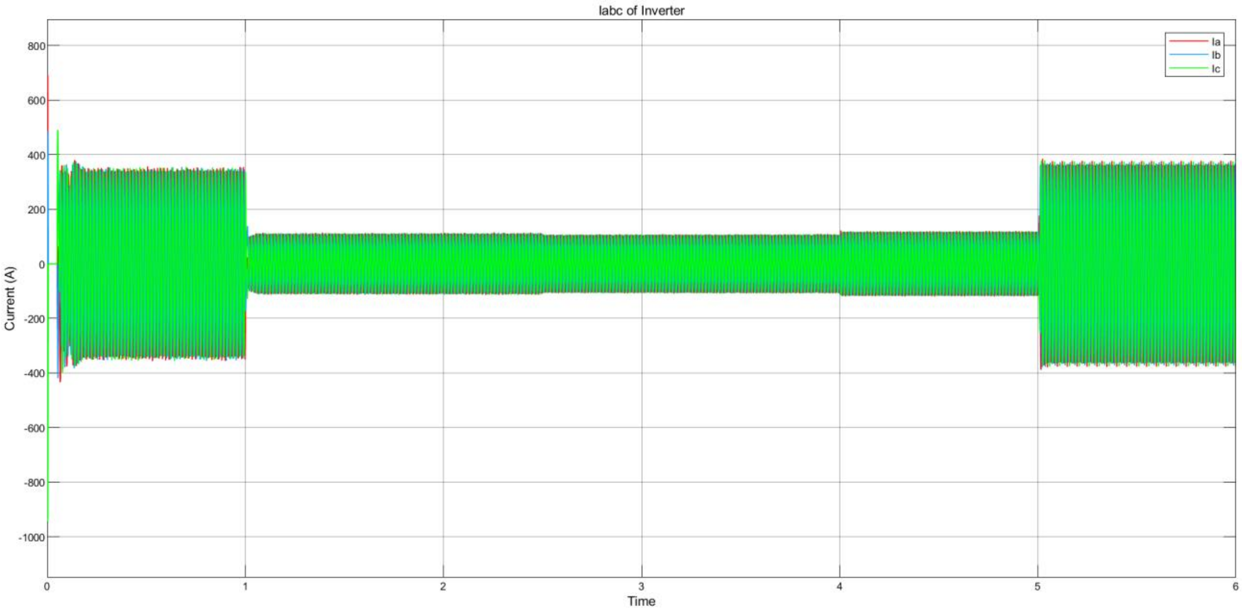

Figure 6. 25: Iabc of inverter

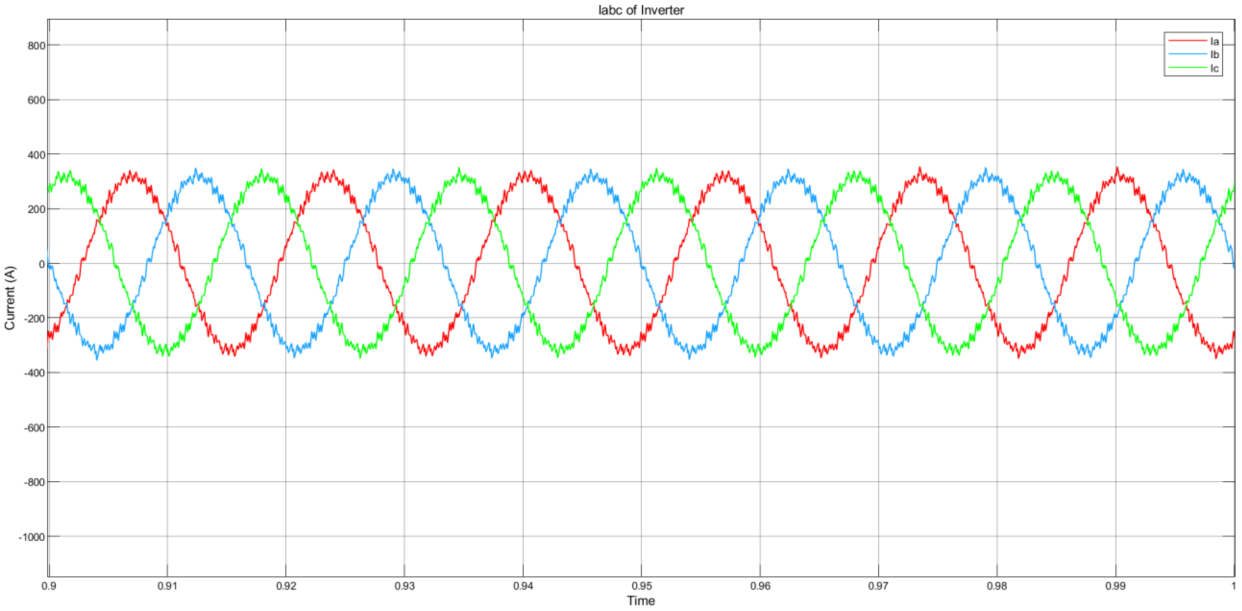

Figure 6. 26: Iabc of inverter – zoomed in

At high values of irradiance, we have a high value of current. At lower values of irradiance, current is low. These therefore affects power. We have an almost perfect sinusoidal waveform of currents.

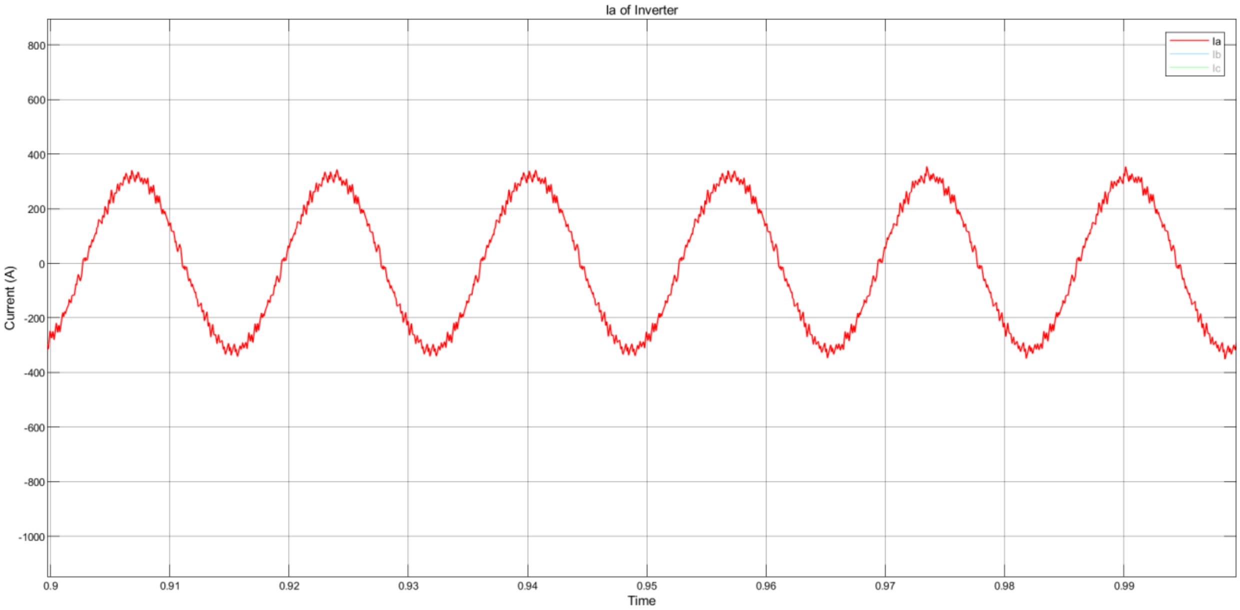

Figure 6. 27: Ia of inverter

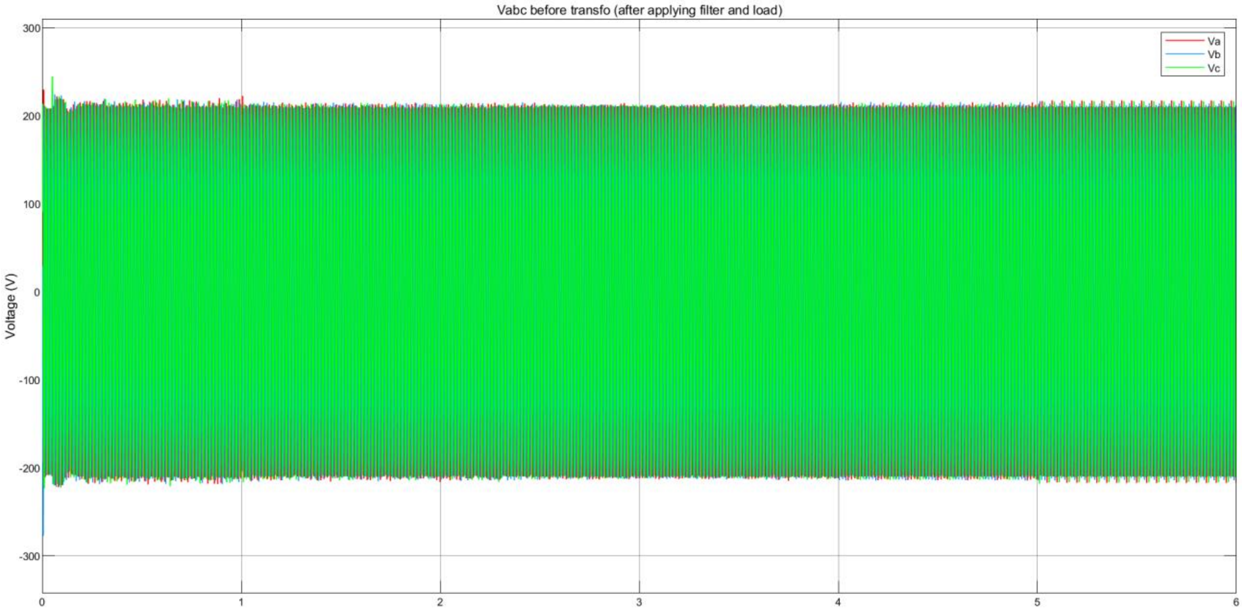

Figure 6. 28: Vabc after applying filter

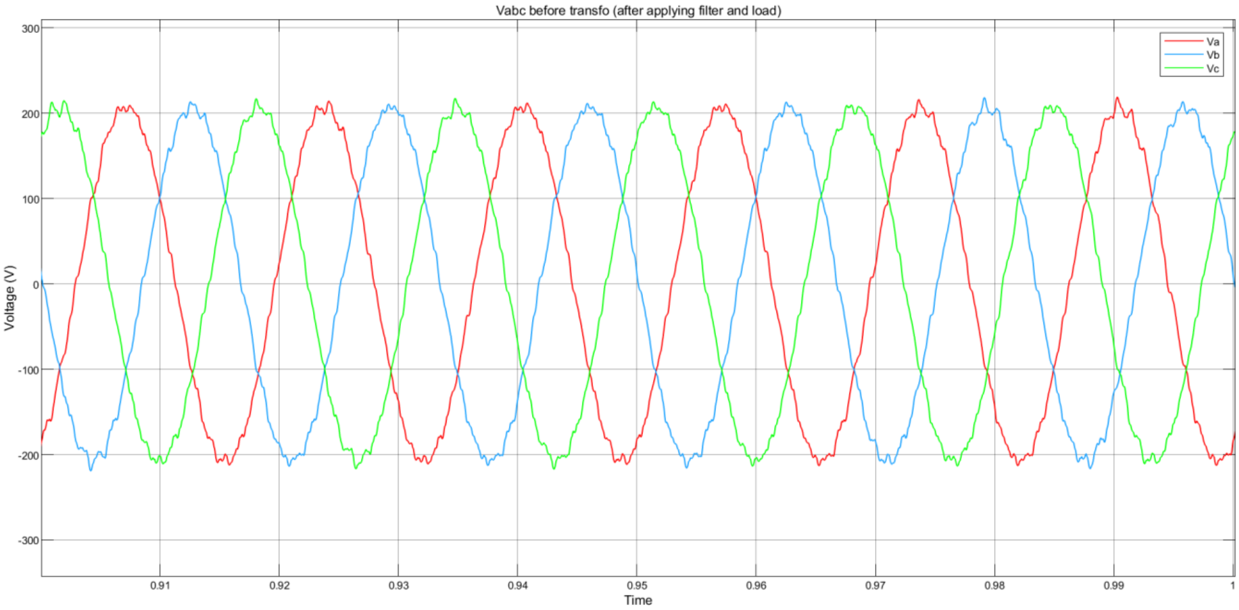

Figure 6. 29: Vabc after applying filter

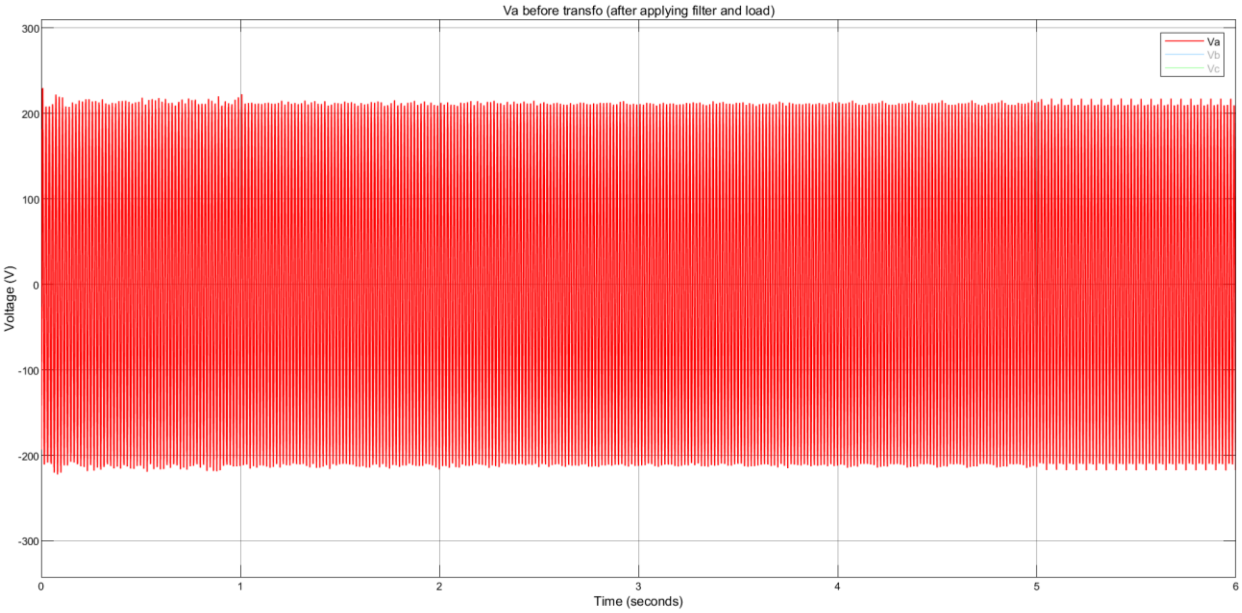

Figure 6. 30: Va after applying filter

After application of an LC filter, we now have a pure sine wave voltage.

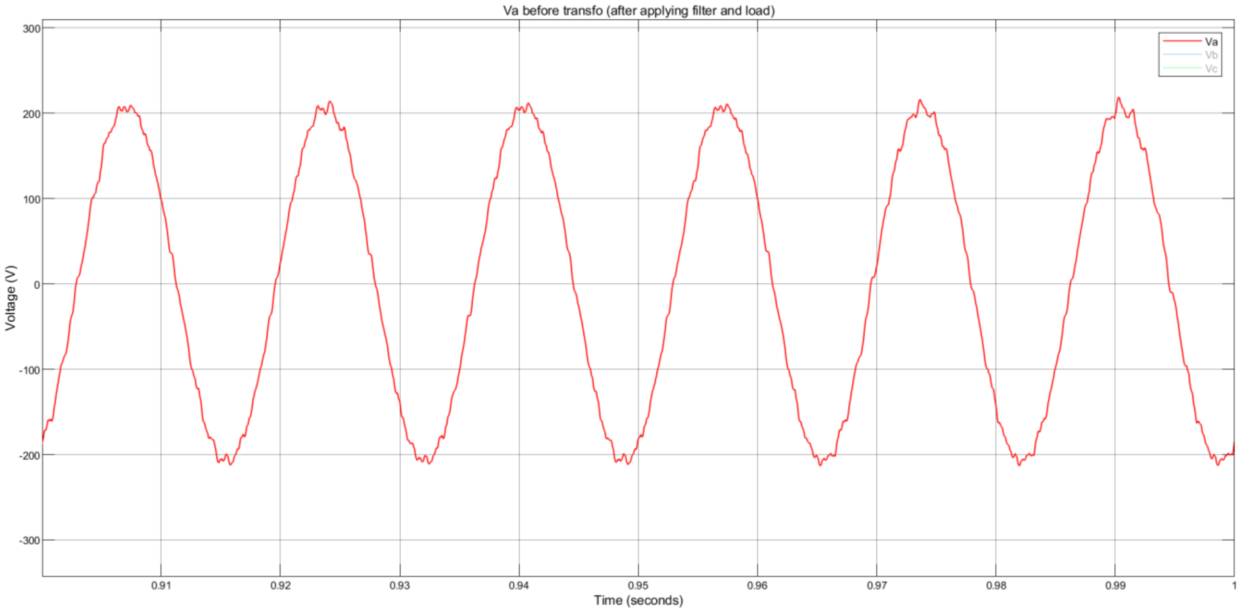

Figure 6. 31: Va after applying filter –Zoomed in

6.6. Conclusion

For grid connected PV system i.e., HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) application of PV systems where we deal with large values of power (in thousands, tens of thousands or even hundreds of thousands of Watts), the choice of MPPT does not make a huge difference, a difference of ±1KW in power for the different MPPT technique has little to no influence on the overall system as seen in our simulation. If we have to nit-pick in choosing, we will go for sliding mode control as it has proven to be the best option in our previous chapter. We won’t go wrong with any of the other two option if they are to be chosen too.

Change in irradiance has a noticeable effect on our PV system. A decrease in irradiance led to a decrease in current and consequently a decrease in power. An increase in irradiance ahs the reverse effect i.e., increase in current thus a subsequent increase in power.

Change in Temperature has no noticeable influence on power. Change in either irradiance or temperature has no effect on voltage. Voltage remained constant all through.

GENERAL CONCLUSION

Solar power energy production is highly becoming the most sought-after method of generating electricity. With the immense availability of renewable solar energy and its great increase due to global warming and fast-growing technology, we can therefore predict its great growth in the years to come. The work presented in this thesis focused on tracking the maximum power of a photovoltaic system through the application of Maximum Power Point Tracking controls. We analysed that a photovoltaic cell is a generator whose IV characteristic is nonlinear. Consequently, with the same lighting, the power delivered is different depending on the load and the MPPT controller. The MPPT regulation therefore, makes it possible to control the static converter that connects the load and the photovoltaic generator in such a way that the load is continuously supplied with maximum power.

At the beginning of this thesis, we presented the generalities and notions surrounding solar energy particularly solar energy potential in African countries such as Algeria, Zambia, and Nigeria. The potential of solar energy being one of the most used sources for power generation is undoubtedly high because it gives the possibility to have different systems including hybrid systems. It is however very expensive to set up, especially for large-scale consumption of energy.

The existence of different Photovoltaic models gave us the ability to analyse the system on a larger scale; from the modeling and simulation result of the cell, we analysed the cell characteristic curves. We analysed the effects of varying temperature and irradiance therefore to obtain high power a solar panel must function at a high value of irradiance and a corresponding low temperature. Through this simulation, we review and conclude that the single diode model is the closest to a real-life model however, the ideal model gives higher power due to lack of resistance.

We expanded our work to power electronics that play a very important role in transforming voltage and current either DC-DC or DC-AC. This expansion comprises of converters such as the Boost converter that according to the results of our simulation stepped up the fluctuating voltage of our solar panel to a higher DC voltage. We also used the power electronics converters in our final chapter through our inverter that played the role of a DC-AC converter as well as a filter through its controller.

The modelling of various MPPT control systems gave us a wide range of methods used for tracking, through this, we analysed that our MMPT taken as an electronic DC-DC converter controller optimized and adjusted the PV voltage to generate the most power. We also conclude that the sliding mode control is the best when connected to load because it gave a higher value of power and had the fastest settling time as compared to PO and Incremental conductance. For HVAC and HVDC application, it doesn’t have as much effect.

In addition, our PV system was then connected to the grid this is for the purpose of adding more energy to the grid, especially during peak load. This paper presents an easier approach for modelling a grid connected photovoltaic (PV) system using MATLAB/Simulink. The proposed model consists of a PV array, Pulse Width Modulation generator, inverter and an LC filter. Modelling of these components has been described and demonstrated in detail. The impact of solar irradiance and temperature on the overall power generation of a grid connected PV system has been studied. Control to maintain constant voltage at the inverter output and for synchronization of the output frequency with the electric utility grid, phase locked loop and regulators have been designed and modelled. The simulation method is easier and can be implemented in practice to study system performance for different conditions of temperature and solar irradiance levels Therefore, we conclude that a PV system serves as another source of energy for electrical grid

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