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Study of a Grid-Connected Photovoltaic System

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Dedication

- To my beloved Parents Mr and Mrs JANGA,
- To my beloved brothers, friends, relatives and loved ones,
- To the Electrical Engineering Department Staff and the Power Systems Engineering class of 2018/2019.

Special dedication

I DEDICATE THIS WORK TO THE MEMORIES OF MY LATE FRIEND, BROTHER, PROJECT PARTNER AND A TRUE COMBATRIOT MR. NDUDZO PROSPER.

MAY HIS SOUL REST IN PEACE.

JANGA ADMIRE

Abstract

The human activities contribute to the global warming of the planet. As a result, every country strives to reduce carbon emissions. The world is facing not only the depletion of fossil fuels, but also its rising prices which causes the worldwide economic instability. Numbers of efforts are being undertaken by the Governments around the world to explore alternative energy sources and to achieve pollution reduction. Solar electric or photovoltaic technology is one of the biggest renewable energy resources to generate electrical power and the fastest growing power generation in the world. The main aim of this work is to analyse the interface of photovoltaic system connected to the utility grid, the power electronics interface and the method to track the maximum power point (MPP) of the solar panel. The first chapter consists of different renewable energy technologies. The second chapter describes the application of the PV system in general. The third chapter outlines the system topology and the different standard requirement when having grid-connected PV system. Then main emphasis is to be placed on the photovoltaic system, the modelling and simulation photovoltaic array, the MPP control and the DC/DC converter will be analysed and evaluated. The step of modelling with MATLAB and Simulink of the photovoltaic system is shown respectively and simulation results are provided. The Simulink model of the PV could be used in the future for extended study with different DC/DC converter topology. Optimization of MPPT algorithm can be implemented with the existing Photovoltaic and DC/DC converter.

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List of Abbreviations

PV: Photovoltaic

Rs: Array series resistance

Rp: Array parallel resistance

Ns: Number of series modules

Np: Number of parallel modules

I: Output current of the array

V: Output voltage of the array

Im: Module current

A: Diode ideality constant

Vt: Thermal voltage

Ncs: Number of cells connected in series

Q: Electron charge k Boltzmann constant

T: Temperature of the P-N junction in Kelvin's

Ipv: Photovoltaic current

Io: Reverse leakage current of the diode

Ipvn: Nominal photovoltaic current at 25°C and 1000 W/m2

Ki: Current temperature confidents

Kv: Voltage temperature confidents

G: Irradiance (W/m2)

Gn: Irradiance at nominal conditions

Iscn: Short circuit current at nominal conditions

Vocn: Open circuit voltage at nominal conditions

∆ T: Difference between the actual and the nominal temperatures in Kelvin's D Duty-Cycle

MPP: Maximum Power Point

MPPT: Maximum Power Point Tracking

P&O: Perturbation and Observation

ICT: Incremental conductance technique

VSC: Voltage Source Converter PWM Pulse Width Modulation

General Introduction

Energy resources and their utilization will be a prominent issue of this century. The problems of natural resource depletion, environmental impacts, and the rising demand for new energy resources have been discussed fervently in recent years. Grid-connected photovoltaic (PV) power systems have been sustaining an exponential growth rate during the past decade. This steep growth is driven by a growing concern about climate change, rebates and tax incentives, and reduction in PV system cost. The main disadvantage of solar energy based electrical power supply is that power generation is not constant throughout the day, as it always changes with atmospheric conditions. Further, the efficiency of solar energy conversion to electrical energy is very low, only in the range of 9-17%. Therefore, maximum power point tracking (MPPT) is an essential part of a grid-tied solar PV system to ensure that maximum available power is always extracted out of the PV panel at all conditions and steered to the AC grid, considered as an infinite sink of power ideally. This feature has an essential role in dynamic response and efficiency of the photovoltaic system, in literature, different MPPT algorithms are introduced and among them the “Perturb and Observe (P&O)” and “Incremental Conductance” are mostly used, on the other hand, some MPPTs are more rapid and accurate and thus more impressive, which need special design and familiarity with specific subjects such as fuzzy logic, or neural network methods. Grid connected PV systems feed electricity directly to the electrical network, operating parallel to the conventional electric source. The simplest grid-connected PV system contains a PV array and an inverter unit used for residential purpose to generate clean electricity near the point of use. One of the main technical barriers that can ultimately limit further PV penetration is the fast variations in the PV system’s output power induced by cloud transients. Such events are known to cause voltage fluctuations which may lead to excessive operations of voltage regulation equipment and light flickering. Solar irradiance variability, which can be easily recorded using a pyrometer and a data logger, is used in numerous studies to assess the AC power injected into the grid by PV systems. But in reality, the two variables are not perfectly proportional with one another, nor synchronized in time due to delays within the inverter circuit elements and controls. As a consequence, computer models that accurately simulate the dynamic behaviour of PV systems under moving clouds would thus be of high value. In this thesis, a dynamic MATLAB/Simulink model of a three phase grid-connected PV system that can be used to predict the deviations in AC power output under variable solar irradiance is presented. The commonly used “Incremental Conductance technique for Maximum Power Point Tracking (MPPT) is used in the presented model.

CHAPTER 1:

Renewable Energy Technologies

1.1 INTRODUCTION

The acceleration of greenhouse gas emissions indicates a mounting threat of runaway climate change, with potentially disastrous human consequences. The utilization of Renewable Energy Sources (RES) together with improvement of the energy end-use efficiency can contribute to the reduction of primary energy consumption, to the mitigation of greenhouse gas emissions and thereby to the prevention of dangerous climate change.

The not utilized potential of biomass, solar, hydro, wind, ocean, nuclear and geothermal source is still high. However, in the recent years due significant public incentives in the form of feed-in-tariff, in many countries of the world the development of the sector has progressively increase.

Moving towards a low-carbon economy requires a public sector able to identify and support the economic opportunities. In particular, the local public sector can play a strategic role as manager of the territory and last implementer of public policies. Therefore, in the field of sustainable energy, it is essential to reinforce the capacities of the local public sector through the empowerment of its workforce.

This chapter is going to elaborate all forms of energy, their advantages and disadvantages with respect to the other.

1.1.1 Energy Sources

Non-renewable: A non-renewable resource is a limited natural resource that cannot be re-made or re-grown in a short amount of time at a scale comparable to its consumption.

Figure 1.1 Non-renewable resources

Renewable: Renewable resources are unlimited natural resources that can be replenished in a short period of time.

Figure 1.2 Renewable resources

1.1.2 Renewable Energy Sources

Renewable energy is energy generated from natural resources— such as sunlight, wind, rain, tides and geothermal heat—which are renewable (naturally replenished). Solar energy, Wind, Hydropower, Biomass, Ocean energy, Geothermal and Waste to Energy.

1.1.3 Wind Energy

Figure 1.3 Wind Energy

The extraction of power from wind began very early in centuries, with wind powered ships, grain mills and threshing machines. Only toward the beginning of this century high-speed wind turbines for generation of electrical power have been developed. The term Wind Turbine is widely used nowadays for a machine with rotating blades that converts the kinetic energy of wind into useful power. Two basic categories of Wind Turbines exist: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT), depending on the orientation of the rotor axis.

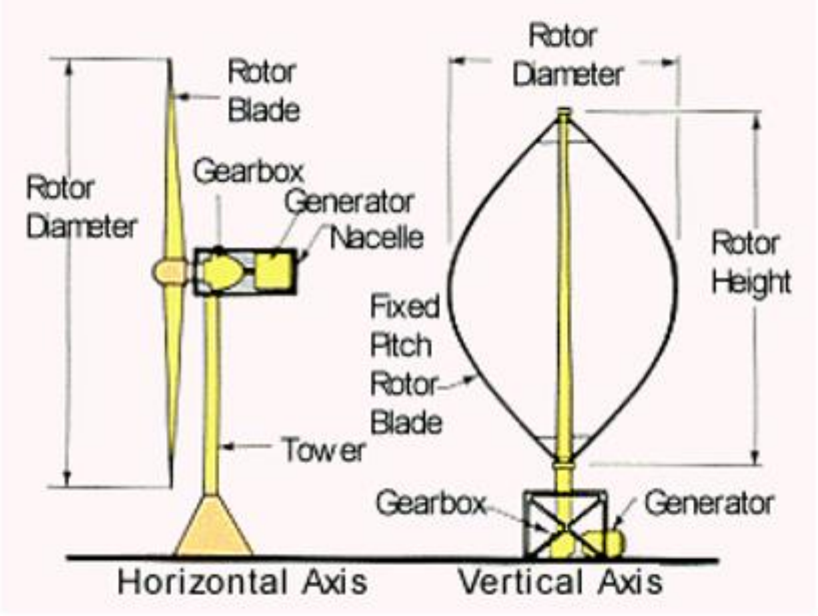


Figure 1.4 Wind Turbine

Nowadays, the major applications of wind energy involve electricity generation, with the wind turbines operating in parallel with utility grid systems or, in more remote locations, in parallel with fossil fuelled engines (hybrid systems). The gain from the exploitation of wind energy is reduced fossil fuel consumption, as well as reduced overall electricity generation costs. Power utilities have the flexibility to accept a contribution of about 20% from wind energy systems. Wind-diesel systems can provide more than 50% fuel saving.

Producing electricity from the wind is a rather new industry. In some countries wind energy is already competitive with fossil and nuclear power, even without accounting for the environmental benefits of wind power. The cost of electricity from conventional power stations does not usually take full account of their environmental impact (acid rain, oil slick clean up, the effects of climate change, etc.). Wind energy production continues to improve in ways that reduce cost and improve efficiency.

1.1.3.1 Modern Wind Turbines

1.1.3.2 Pros

- Omni-directional
- Accepts wind from any direction
- Components can be mounted at ground level
- Ease of service
- Lighter weight towers
- Can theoretically use less materials to capture the same amount of wind.

1.1.3.3 Cons

- Rotors generally near ground where wind is poorer.
- Centrifugal force stresses blades.
- Poor self-starting capabilities.
- Requires support at top of turbine rotor.
- Requires entire rotor to be removed to replace bearings.
- Overall poor performance and reliability.

1.1.3.4 Geothermal Energy

- Geothermal heat is the only renewable energy source created naturally by the Earth itself.
- Approximately 6400km below the Earth's surface is the core, where temperatures can reach 5000°C.
- These reservoirs can be tapped for a variety of uses, such as to generate electricity or to heat buildings.
- The geothermal energy potential in the 10 km of the Earth's crust amounts to 50,000 times the energy of all oil and gas resources in the world.

Figure 1.5 Geothermal Energy

1.1.3.5 Geothermal Electricity generation

High enthalpy geothermal energy is used mostly for electricity production. The typical geothermal system used for electric power generation must yield approximately 10 kg of steam to produce one unit (kWh) of electricity. Production of large quantities of electricity, at rates of hundreds of megawatts, requires the production of great volumes of fluid. Thus, one aspect of a geothermal system is that it must contain great volumes of fluid at high temperatures or a reservoir that can be recharged with fluids that are heated by contact with the rock. The three basic types of geothermal electrical generation facilities are binary, dry steam (referred to as “steam”), and flash steam (referred to as “flash”) when the pressure on hot water (usually above 100°C) is reduced. Electricity production from each type depends on reservoir temperatures and pressures, and each type produces somewhat different environmental impacts. The most common type of power plant to date is a flash power plant with a water cooling system, where a mixture of water and steam is produced from the wells. The steam is separated in a surface vessel (steam separator) and delivered to the turbine, and the turbine powers a generator. In a dry steam plant, steam directly from the geothermal reservoir runs the turbines that power the generator, and no separation is necessary because wells only produce steam. Recent advances in geothermal technology have made possible the economic production of electricity from lower temperature geothermal resources, at 100°C to 150°C. Known as “binary” geothermal plants, these facilities reduce geothermal energy’s already low emission rate to near zero. In the binary process, the geothermal water heats another liquid, such as isobutene (typically n-pentane), that boils at a lower temperature than water and has high vapour pressure at low temperatures when compared to steam.

Geothermal Power Plant Technologies

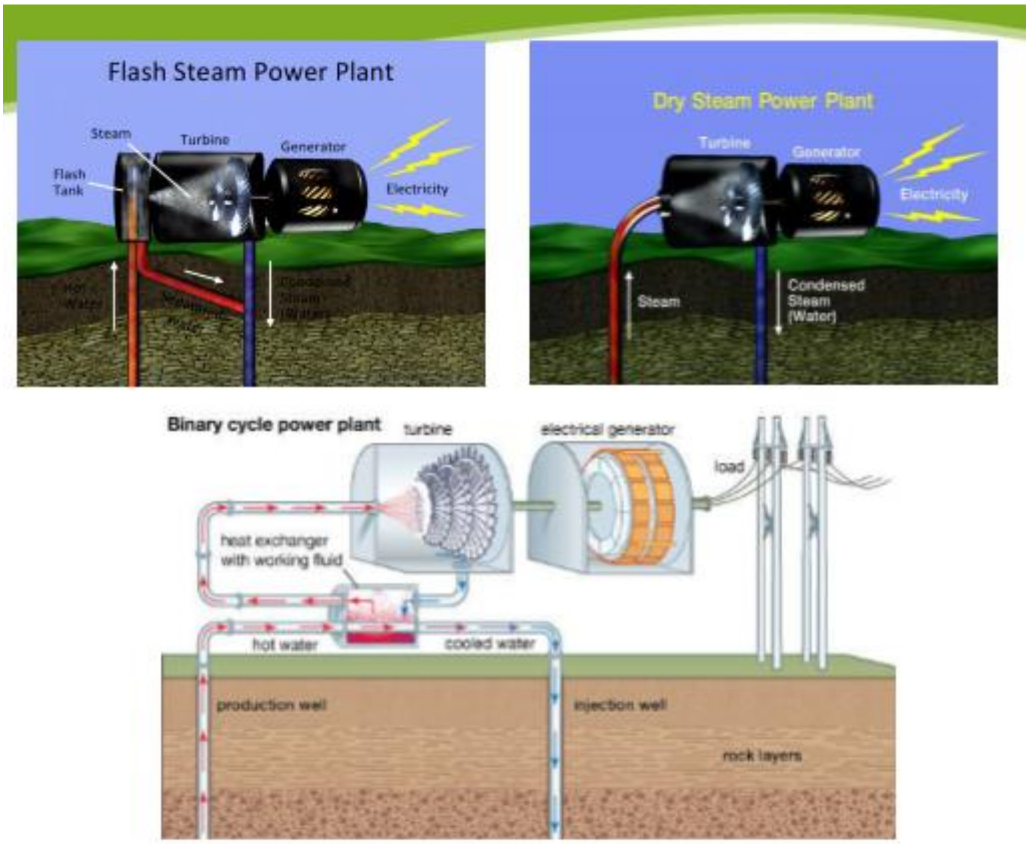


Figure 1.6 Geothermal Technologies

1.1.3.6 Environmental Impacts of geothermal energy

Geothermal energy is defined as natural heat from within the Earth, captured for production of electric power, space heating or industrial steam. It is present everywhere beneath the Earth’s surface, although the highest temperature, and thus the most desirable, resources are concentrated in regions of active or geologically young volcanoes.

It is a clean, renewable resource because the heat emanating from the interior of the Earth is essentially limitless. The source of geothermal energy, the Earth’s heat, is available 24 hours a day, 365 days a year. Solar and wind energy sources, in contrast, are dependent upon a number of factors, including daily and seasonal fluctuations and weather variations. For these reasons, electricity from geothermal energy is more consistently reliable, once the resource is tapped, than many other forms of electricity. The heat continuously flowing from the Earth’s interior is estimated to be equivalent to 42 million megawatts of power (Heat balance from Stacey and Loper, 1988). One megawatt can meet the power needs of about 1,000 homes.

The thermal energy of the Earth is therefore in great abundance and practically inexhaustible, but it is very dispersed, rarely concentrate and often at depths too great for industrial exploitation. So far our utilization of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid phase or steam) to ‘transfer’ the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources.

The environmental impact of the use of geothermal heat is fairly small and controllable. In fact, geothermal energy produces minimal air emissions. Emissions of nitrous oxide, hydrogen sulphide, sulphur dioxide, ammonia, methane, particulate matter, and carbon dioxide are extremely low, especially when compared to fossil fuel emissions.

Yet, both water and condensed steam of geothermal power plants also contain different chemical elements, among which arsenic, mercury, lead, zinc, boron and sulphur, whose toxicity is obviously depending on their concentration. However, the most part of such elements remains in solution in the water that reinjected into the same rock reservoir from which it has been extracted as hot water or steam.

The binary geothermal plant, along with the flash/binary plant, produce nearly zero air emissions.

In the direct use of heat from hot geothermal water, the impact on the environmental is negligible and can be easily mitigated by adopting closed-cycle systems, with extraction and final reinjection of the fluid into the same geothermal reservoir.

The economic aspect of using of hot waters still represents a limitation to their wider dissemination in the energy sector. In fact, the economic benefit derives from their prolonged use over the years at low operating costs vs. initial investments which may be considerable.

1.1.4 Hydropower

Hydroelectric power comes from water at work, water in motion. Nature ensures that water is a renewable resource.

Small hydro is the largest contributor of electricity from renewable energy sources, both at European and world level. At world level, it is estimated that there is an installed capacity of 47.000 MW, with a potential - technical and economical - close to 180.000 MW.

Small scale Hydro Power (SHP) is mainly "run of river", i.e. not involving significant impounding of water and therefore not requiring the construction of large dams and reservoirs, though where these exist and can be utilised easily they do help. There is no general international consensus on the definition of SHP; the upper limit varies between 2.5 and 25 MW in different countries, but a value of 10 MW is becoming generally accepted and has also been accepted by ESHA (the European Small Hydro Association).

The definition for SHP as any hydro systems rated at 10 MW or less will therefore be used herein. SHP can be further subdivided into “mini hydro”, usually defined as those systems with capacity < 500kW, and “micro hydro” for systems with capacities < 100kW. Whichever size definition is used, SHP is one of the most environmentally benign forms of energy generation, based on the use of a non-polluting renewable resource, and requiring little interference with the surrounding environment.

It also has the capacity to make a significant impact on the replacement of fossil fuel, since unlike many other sources of renewable energy, SHP can generally produce some electricity at any time on demand (i.e. it needs no storage or backup systems), at least at times of the year when an adequate flow of water is available, and in many cases at a competitive cost with fossil fuel power stations

1.1.4.1 Hydropower Plants

Figure 1.7 Hydro Power plants

1.1.4.2 Pumped Storage Hydropower Plant

When demand for electricity is low, a pumped storage facility stores energy by pumping water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir to generate electricity.

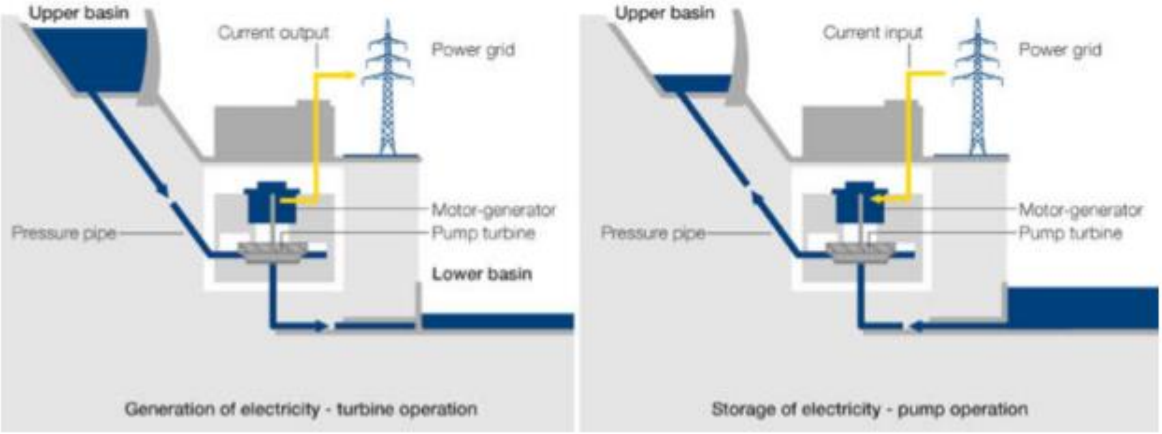


Figure 1.8 Pumped Storage Hydropower Plant

1.1.4.3 Head and flow

The objective of a hydro power scheme is to convert the potential energy of a mass of water, flowing in a stream with a certain fall, into electric energy at the lower end of the scheme, where the powerhouse is located. The vertical fall of the water, known as the “head”, is essential for hydropower generation; fast flowing water on its own does not contain sufficient energy for useful power production except on a very large scale, such as offshore marine currents. Hence two quantities are required: a flow rate of water **Q**, and a head **H**. It is generally better to have more head than more flow, since this keeps the equipment smaller. The **Gross Head** (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head. The **Flow Rate** (Q) in the river is the volume of water passing per second, measured in m3/sec. For small schemes, the flow rate may also be expressed in litres/second where 1000 litres/sec is equal to 1 m3/sec. According to the head, schemes can be classified in three categories: High head: 100 m and above Medium head: 30 - 100 m, Low head: 2 - 30 m. These ranges are not rigid but are merely means of categorising sites. Schemes can also be defined as Run-of-river schemes. Schemes with the powerhouse located at the base of a dam and Schemes integrated on a canal or in a water supply pipe. In general high-head sites are less expensive to develop than low-head sites, because for the same power output the flow through the turbine and required hydraulic structures will be smaller. In a river with a comparatively steep gradient over part of its course, the level difference can be utilised by diverting all or part of the flow and returning it to the river once it has passed through the turbine. The water can be brought from the intake directly to the turbine through a pressure pipe.

Figure 1.9 Head and Flow

1.1.4.4 Advantages and disadvantages of small-hydro

Small-scale hydropower is one of the most cost-effective and reliable energy technologies to be considered for providing clean electricity generation. In particular, the key advantages that small hydro has over wind, wave and solar power are: A high efficiency (70 - 90%), by far the best of all energy technologies. A high capacity factor (typically >50%), compared with 10% for solar and 30% for wind A high level of predictability, varying with annual rainfall patterns Slow rate of change; the output power varies only gradually from day to day (not from minute to minute). A good correlation with demand i.e. output is maximum in winter It is a long-lasting and robust technology; systems can readily be engineered to last for 50 years or more. It is also environmentally benign. Small hydro is in most cases “run-of-river”; in other words, any dam or barrage is quite small, usually just a weir, and little or no water is stored. Therefore, run-of-river installations do not have the same kinds of adverse effect on the local environment as large-scale hydro.

1.1.5 Bioenergy

1.1.5.1 Biomass

- One of the promising sources of renewable energy is biomass.
- Biomass is the feed stock used to produce bioenergy.
- Bioenergy is a general term for energy derived from materials such as straw, wood, or animal wastes.
- Such materials can be burned directly to produce heat or power, and also can be converted into liquid bio fuels.

Figure 1.10 Bio Energy

1.1.5.2 Types of Biomass

Figure 1.11 Different types of Biomass

“On average, biomass is made of 75% carbohydrates and 25%lignin”.

Biomass Direct Combustion

There are two main components of a combustion–based biomass plant:

- Biomass-fired boiler.
- Steam turbine.

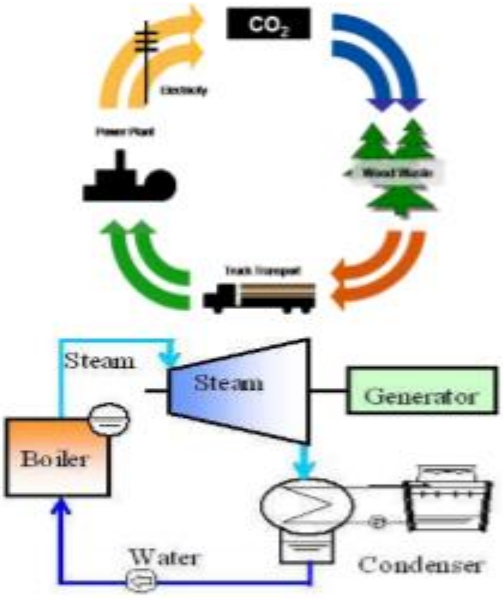


Figure 1.12 Biomass fired boiler

1.1.5.3 Anaerobic Digestion

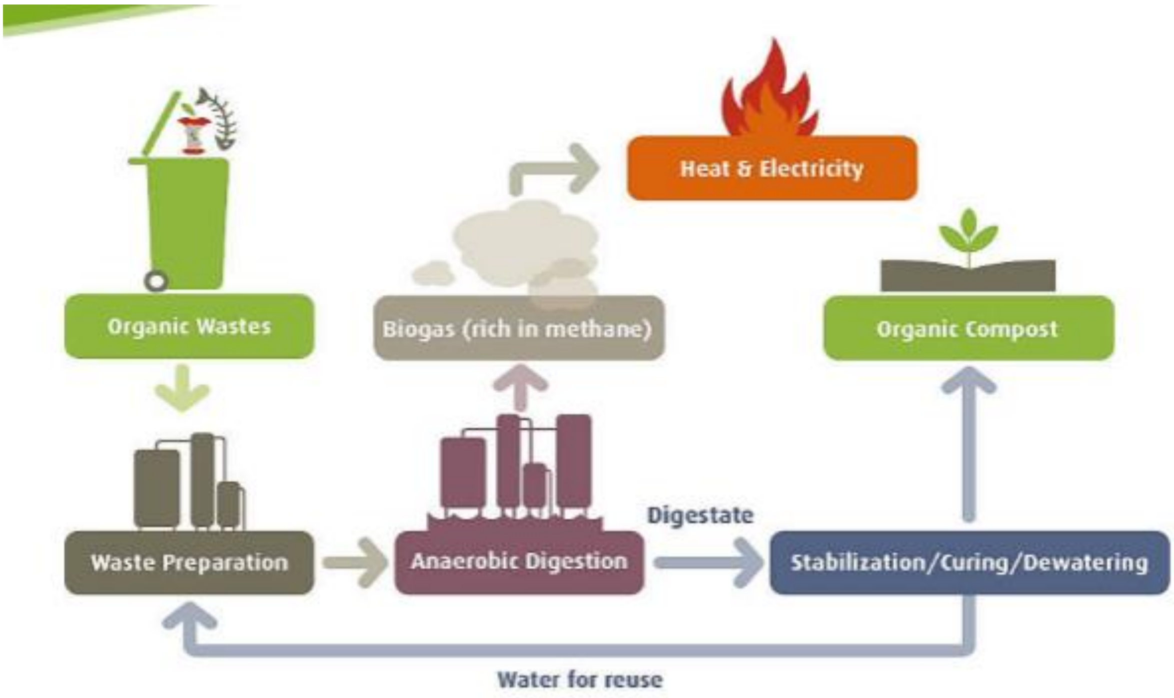


Figure 1.13 Anaerobic Digestion

1.1.5.4 Biodiesel and Bioethanol Production

- Biodiesel refers to a vegetable oil or animal fat based diesel fuel which is typically made by chemically reacting lipids (vegetable oil, soybean oil, animal fat) with an alcohol producing fatty acid esters.
- Bioethanol is an alcohol made by fermentation, mostly from carbohydrates produced in sugar or starch crops.
- Cellulosic biomass, derived from non-food sources, such as trees and grasses, is also being developed as a feed stock for ethanol production

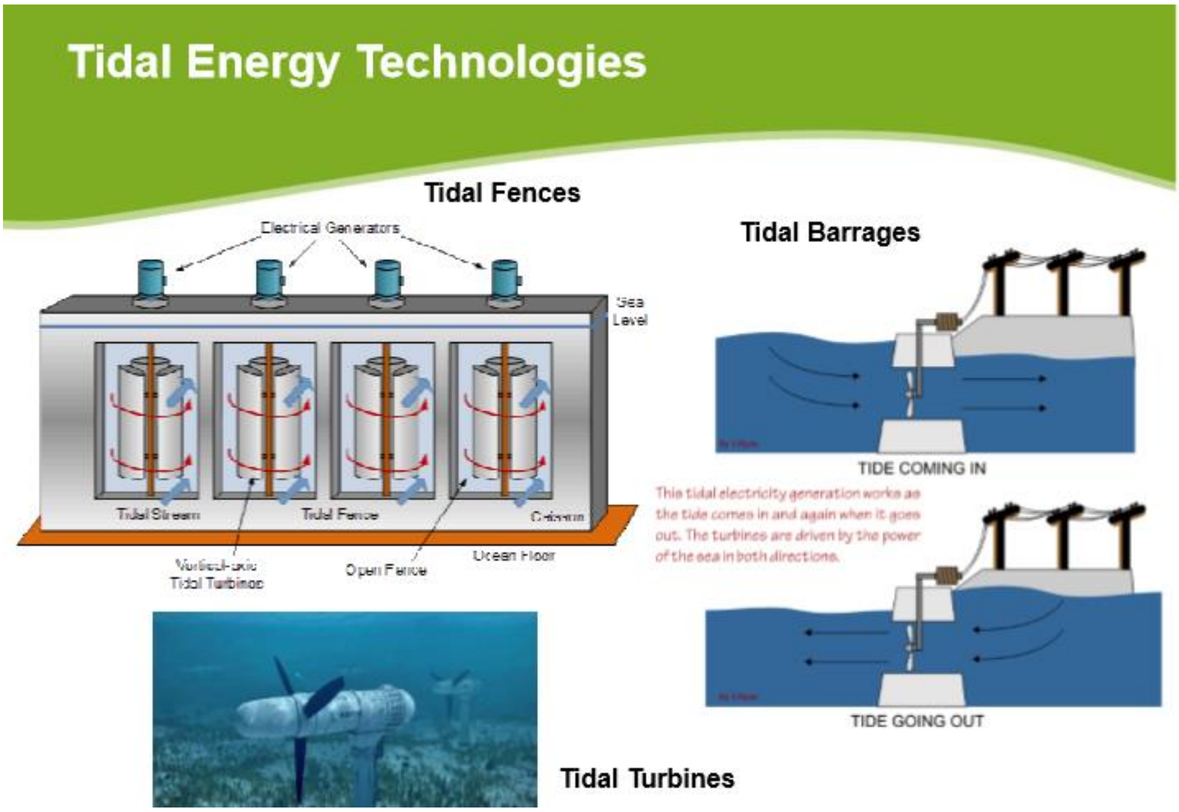
1.1.5.5 Advantages and disadvantages of Bio Energy.

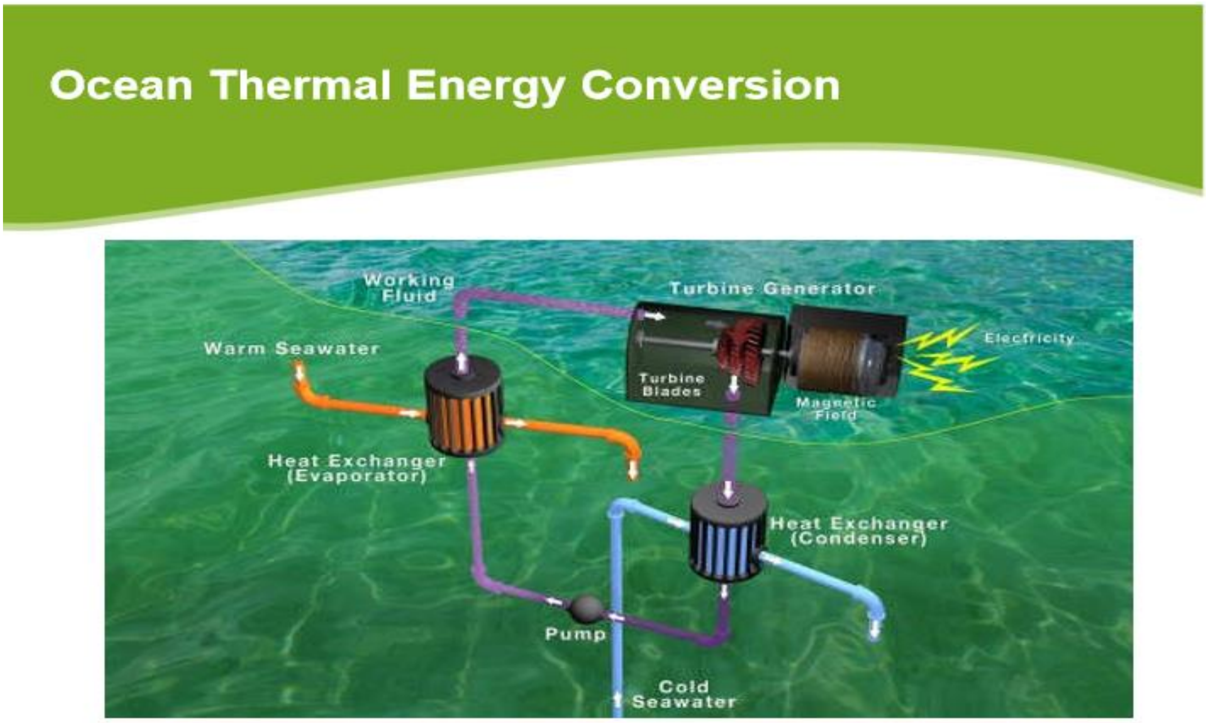
1.1.6 Marine and Hydrokinetic Energy

- Marine and hydrokinetic energy systems, a new generation of water power technologiesoffersthepossibilityofgeneratingelectricityfromwaterwithout the need for dams and diversions.
- The ocean can produce two types of energy:
- Thermal energy from the sun’s heat.
- Mechanical energy from the tide sand waves

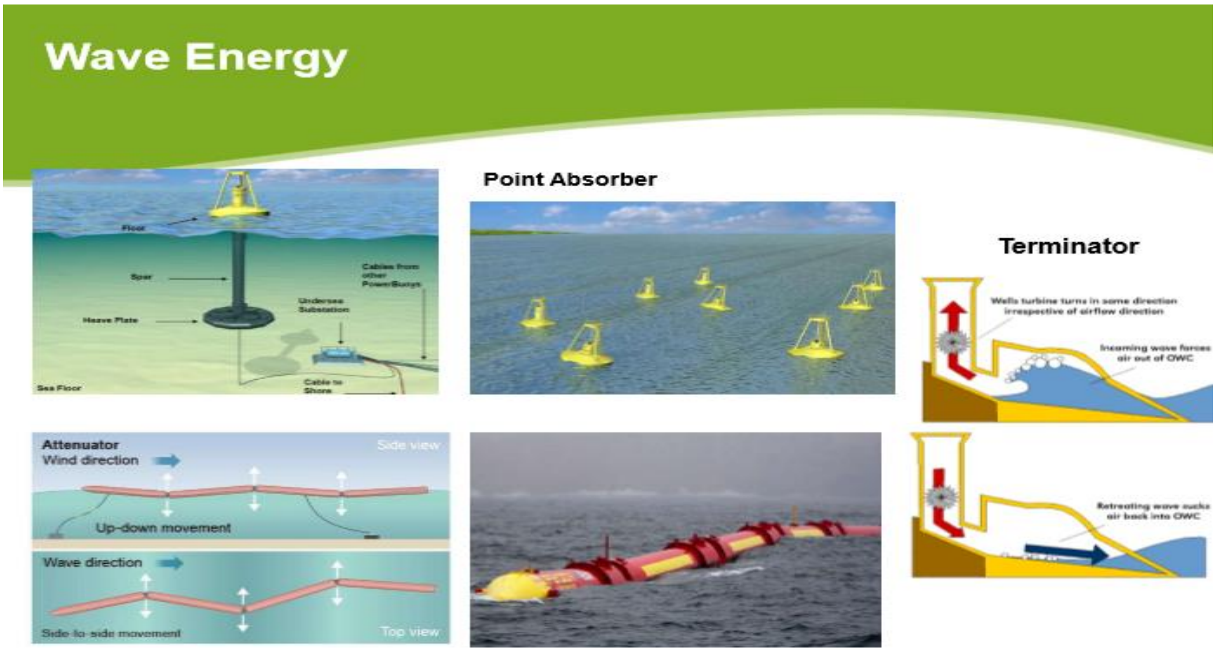
The three most well-known generating technologies for deriving electrical power from the ocean are:

- Tidal power, Wave power and Ocean thermal energy conversion(OTEC).





Ocean Thermal Energy Conversion



Wave Energy

Figure 1.14 Tidal Energy Technologies

1.1.7 Nuclear energy

At nuclear power plants, the heat to make the steam is created when atoms split apart — called fission. When atoms split apart, they release heat. When the process is repeated over and over, it is called a chain reaction. In a nuclear power plant, uranium is the material used in the fission process.

The heat from fission boils water and creates steam to turn a turbine. As the turbine spins, the generator turns and its magnetic field produces electricity. The electricity can then be carried to your home, so you can work on the computer, watch television or make toast!

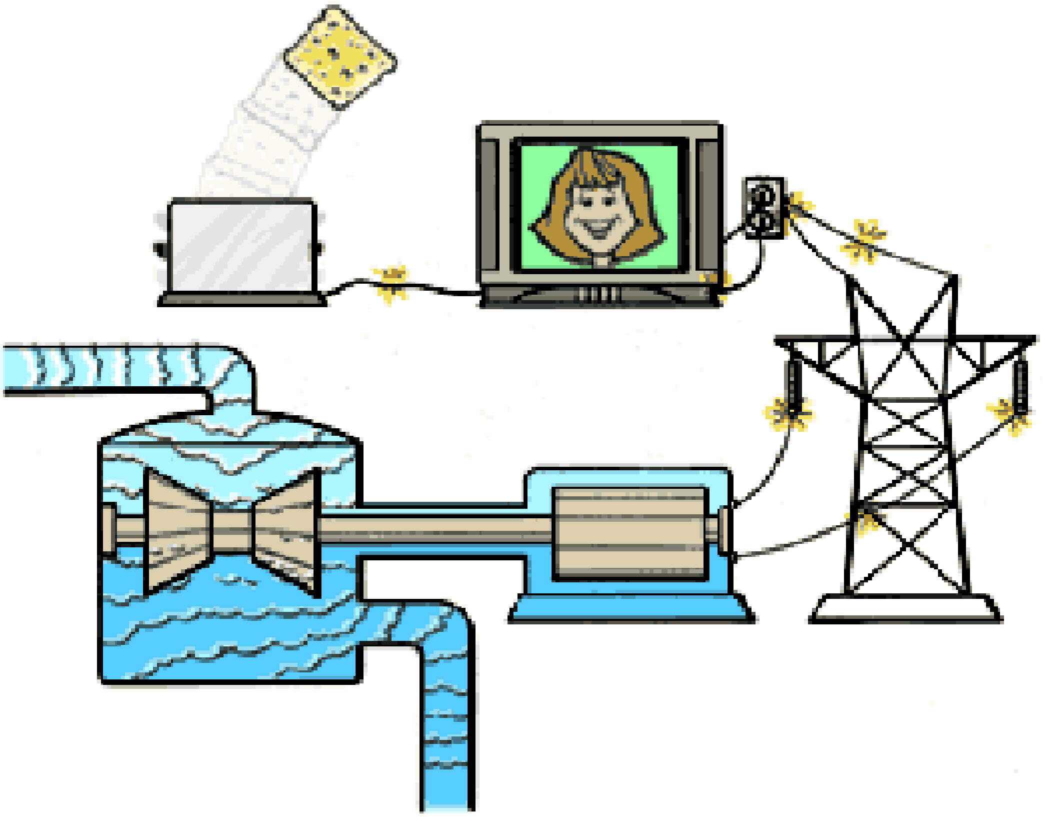


Figure 1.15 Nuclear Energy

1.1.7.1 Nuclear Reactors

Nuclear power plants are very complex. There are many different buildings at the site and many different systems. Some of the systems work directly to make electricity. Some of the systems work to keep the plant working correctly and safely. All nuclear power plants have a "containment structure" that holds the reactor. And all plants have deep pools where the nuclear fuel when it is no longer being used can be cooled and stored.

All nuclear power plants make electricity from the steam created by the heat of splitting atoms. But there are two different ways that steam is used.

Pressurized Water Reactors are known as "PWRs." They keep water under pressure so that it heats but does not boil. Water from the reactor and the water that is turned into steam are in separate pipes and never mix.

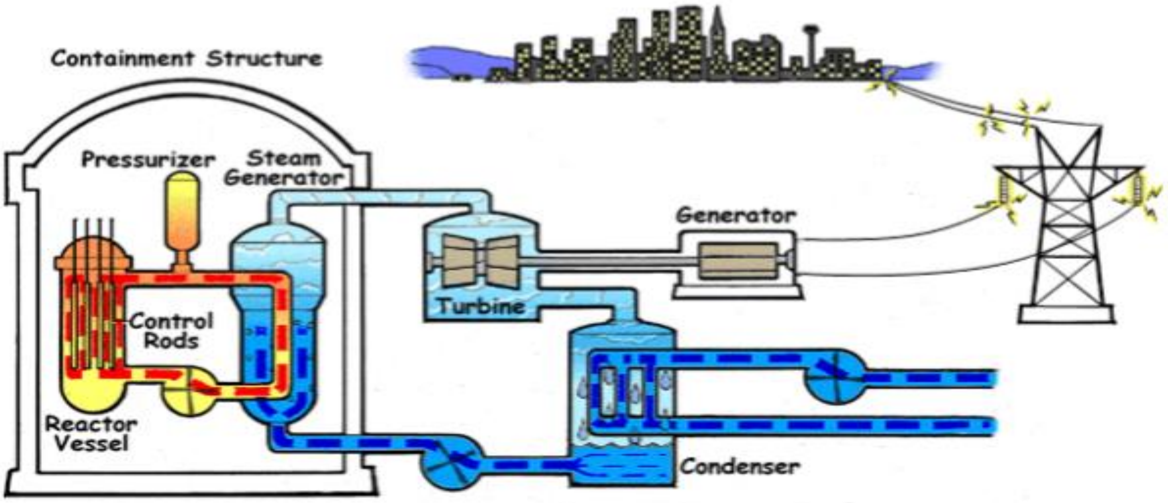


Figure 1.16 Nuclear Reactors

Boiling Water Reactors are known as "BWRs." In BWRs, the water heated by fission actually boils and turns into steam to turn the generator. In both types of plants, the steam is turned back into water and can be used again in the process.

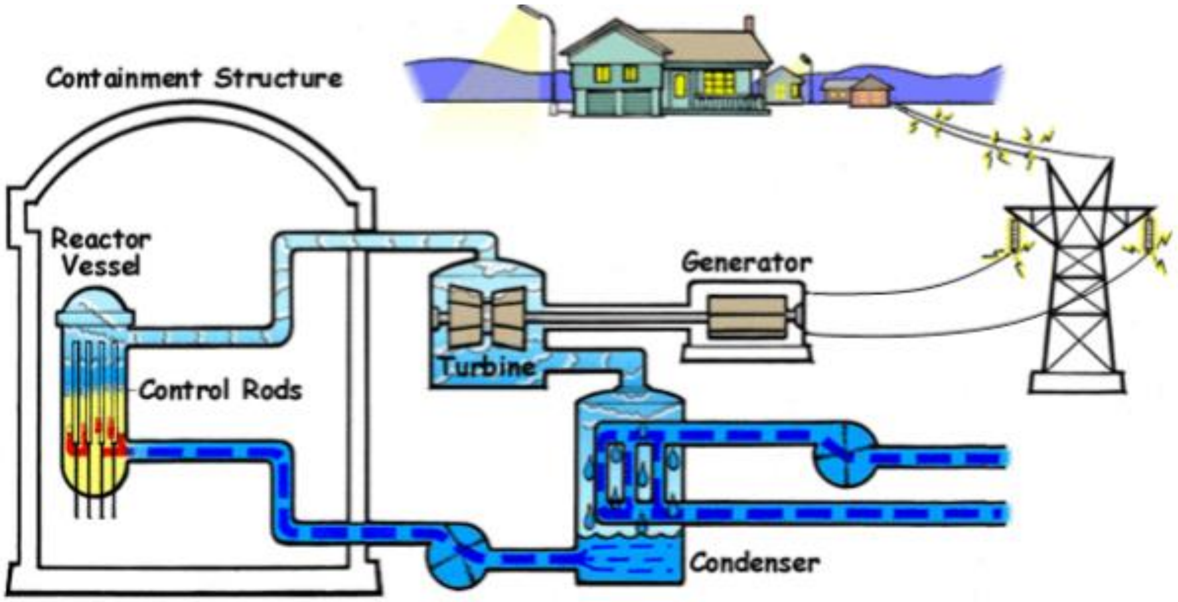


Figure 1.17 Electrical energy generation from nuclear energy

1.1.7.2 Environmental Impacts of Nuclear Energy

In all nuclear power plants, the process of making electricity causes radioactivity. The radioactivity comes from the splitting of the atoms. It must be carefully managed because it can be dangerous if not handled properly. It can damage human cells or cause cancer over time. So all nuclear power plants have many safety systems that protect workers, the public and the environment.

For example, systems allow the fission process to be stopped and the reactor to be shut down quickly. Other systems cool the reactor and carry heat away from it. Barriers keep the radioactivity from escaping into the environment.

In reactors, radioactive material is contained inside small ceramic pellets about the size of the tip of an adult's finger. They are placed in long metal rods inside a reactor vessel, which is enclosed in a concrete and steel containment building. These buildings have walls three to five feet thick!

1.2 Conclusion

The potential of renewable energy sources is enormous as they can in principle meet many times the world’s energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. Renewable energy sources currently supply somewhere between 15 percent and 20 percent of world’s total energy demand. The supply is dominated by traditional biomass, mostly fuel wood used for cooking and heating, especially in developing countries in Africa, Asia and Latin America. We have seen in this chapter a detailed analysis and comparison of the different uses, advantages and disadvantages of using different renewable energy sources for electrical power generation.

CHAPTER 2:

Photovoltaic Technology

2.1 INTRODUCTION

Converting solar energy into electrical energy by PV installations is the most recognized way to use solar energy. Since solar photovoltaic cells are semiconductor devices, they have a lot in common with processing and production techniques of other semiconductor devices such as computers and memory chips. As it is well known, the requirements for purity and quality control of semiconductor devices are quite large. With today's production, which reached a large scale, the whole industry production of solar cells has been developed and, due to low production cost, it is mostly located in the Far East. Photovoltaic cells produced by the majority of today’s largest producers are mainly made of crystalline silicon as semiconductor material. Solar photovoltaic modules are a result of combination of photovoltaic cells to increase their power, are highly reliable, durable and low noise devices to produce electricity. The fuel for the photovoltaic cell is free. The sun is the only resource that is required for the operation of PV systems, and its energy is almost inexhaustible.

A typical photovoltaic cell efficiency is about 15%, which means it can convert 1/6 of solar energy into electricity. Photovoltaic systems produce no noise, there are no moving parts and they do not emit pollutants into the environment. Taking into account the energy consumed in the production of photovoltaic cells, they produce several tens of times less carbon dioxide per unit in relation to the energy produced from fossil fuel technologies.

Photovoltaic cell has a lifetime of more than thirty years and is one of the most reliable semiconductor products. Most solar cells are produced from silicon, which is nontoxic and is found in abundance in the earth's crust. Photovoltaic systems (cell, module, network) require minimal maintenance. At the end of the life cycle, photovoltaic modules can almost be completely recycled. Photovoltaic modules bring electricity to rural areas where there is no electric power grid, and thus increase the life value of these areas.

Photovoltaic systems will continue the future development in a direction to become a key factor in the production of electricity for households and buildings in general. The systems are installed on existing roofs and/or are integrated into the facade. These systems contribute to reducing which is nontoxic and is found in abundance in the earth's crust. Photovoltaic systems (cell, module, network) require minimal maintenance. At the end of the life cycle, photovoltaic modules can almost be completely recycled. Photovoltaic modules bring electricity to rural areas where there is no electric power grid, and thus increase the life value of these areas. energy consumption in buildings. A series of legislative acts of the European Union in the field of renewable energy and energy efficiency have been developed, particularly promoting photovoltaic technology for achieving the objectives of energy savings and CO2 reduction in public, private and commercial buildings. Also, photovoltaic technology, as a renewable energy source, contributes to power systems through diversification of energy sources and security of electricity supply.

By the introduction of incentives for the energy produced by renewable sources in all developed countries, photovoltaic systems have become very affordable, and timely return of investment in photovoltaic systems has become short and constantly decreasing. In recent years, this industry is growing at a rate of 40% per year and the photovoltaic technology creates thousands of jobs at the local level.

2.1.1 PHOTOVOLTAIC BACKGROUND

Solar panels are made up of photovoltaic cells; it means the direct conversion of sunlight to electricity by using a semiconductor, usually made of silicon. The word photovoltaic comes from the Greek meaning “light” (photo) and “electrical” (voltaic); the common abbreviation for photovoltaic is PV. Then PV efficiency increased continuously in the following years, and costs have decreased significantly in recent decades. The main material used in the construction of PV cells is still silicon, but other materials have been developed, either for their potential for cost reduction or their potential for high efficiency. Over the last 20 years the world-wide demand for PV electric power systems has grown steadily. The need for low cost electric power in isolated areas is the primary force driving the world-wide photovoltaic (PV) industry today. PV technology is simply the least-cost option for a large number of applications, such as stand-alone power systems for cottages and remote residences, remote telecommunication sites for utilities and the military, water pumping for farmers, and emergency call boxes for highways and college campuses. PV cells are converting light energy, to another form of energy, electricity. When light energy is reduced or stopped, as when the sun goes down in the evening or when a cloud passes in front of the sun, then the conversion process stops or slows down. When the sunlight returns, the conversion process immediately resumes, this conversion without any moving parts, noise, pollution, radiation or constant maintenance. These advantages are due to the special properties of semiconductor materials that make this conversion possible. PV cells do not store electricity; they just convert light to electricity when sunlight is available. To have electric power at night, a solar electric system needs some form of energy storage, usually batteries, to draw upon.

2.1.2 THE POSITION OF THE SUN

For planning a PV system, it is crucial to know the position of the sun in the sky at the location of the solar system at a given time. In this section we explain how this position can be calculated. Since celestial objects like the sun, the moon and the stars are very far away from the earth it is convenient to describe their motion projected on a sphere with arbitrary radius and concentric to the earth. This sphere is called the celestial sphere. The position of every celestial object thus can be parameterised by two angles. For photovoltaic applications it is most convenient to use the horizontal coordinate system, where the horizon of the observer constitutes the fundamental plane. In this coordinate system, the position of the sun is expressed by two angles that are illustrated in below: The altitude a that is the angular elevation of the centre of the solar disc above the horizontal plane. Its angular range is $a \in [-90^\circ, 90^\circ]$, where negative angles correspond to the object being below the horizon and thus not visible. The azimuth A that is the angle between the line of sight projected on the horizontal plane and due

North. It is usually counted eastward, such that A = 0°, 90°, 180°, 270° correspond to due North, East, South and West, respectively. Its angular range is A ∈ [0°, 360°]. In a different convention also used by the PV community, due South corresponds to 0° and is counted westward, the angles then are in between −180° and 180°. Figure below also shows the meridian, which is great circle on the celestial sphere passing through the celestial North and South poles as well as the zenith.

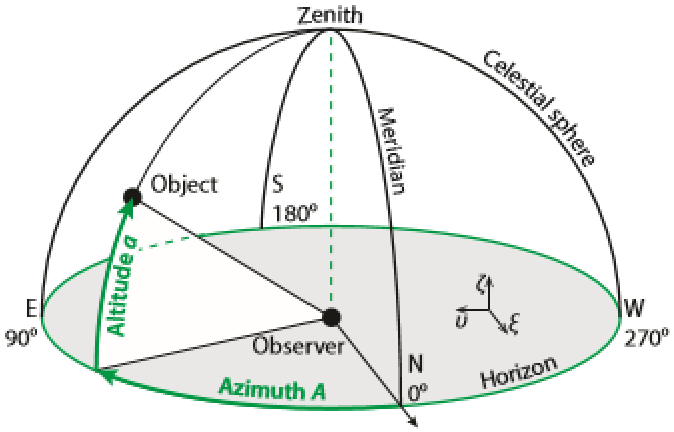
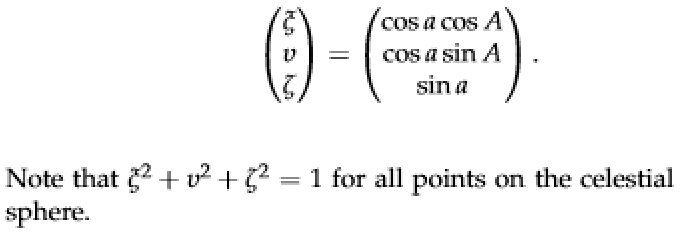


Figure 2.1 Illustrating the definition of the altitude a and the azimuth A in the horizontal coordinate system. Note that North is at the bottom of the figure

Instead of using the spherical coordinates a and A, we also could use Cartesian coordinates, that we here call ξ (xi), υ (upsilon) and ζ (zeta) and that are also depicted in above. The principal direction is parallel to ξ. The Cartesian coordinates are connected to the spherical coordinates via

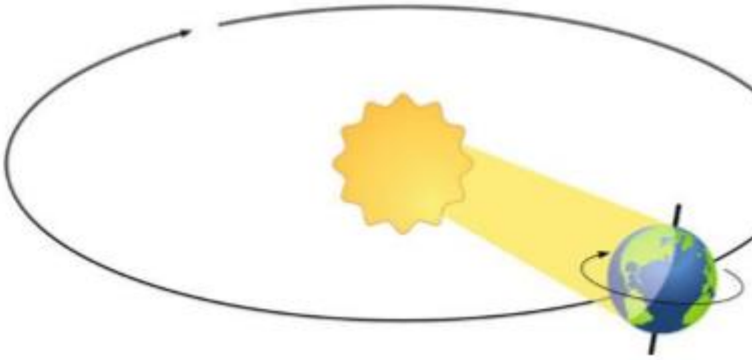


$$\begin{pmatrix} \xi \\ \upsilon \\ \zeta \end{pmatrix} = \begin{pmatrix} \cos a \cos A \\ \cos a \sin A \\ \sin a \end{pmatrix}.$$

Note that $\xi^2 + \upsilon^2 + \zeta^2 = 1$ for all points on the celestial sphere.

2.1.3 Sun geometry

Because of the Earth's orbit and rotation, the position of the sun relative to a solar array is constantly changing. Designers use several geometrical techniques to design an array that will capture the most solar energy possible. The location of the sun is specified by two angles which vary both daily and annually.



2.1.3.1 Solar radiation

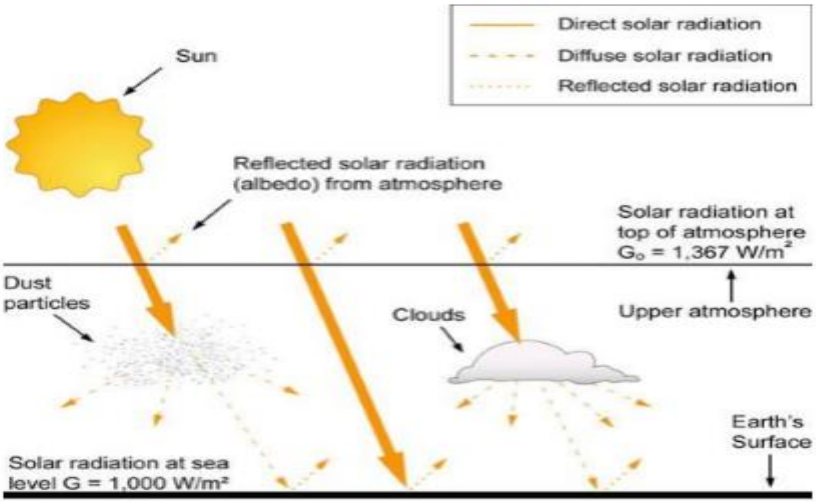


Figure 2.2 Solar radiation

Irradiance is a combination of direct and diffuse radiation and will depend on the albedo (reflected solar radiation) of that particular location. That proportion of solar radiation which is scattered, absorbed or re-emitted in the atmosphere is diffuse radiation. Understandably on a sunny day, this scattered diffuse radiation will contribute only to 10 per cent of visible light, but on a cloudy day there will be much more scattering of the solar radiation reaching the Earth's surface which means the amount of diffuse radiation will be much greater. Air mass will also affect the irradiance at a location

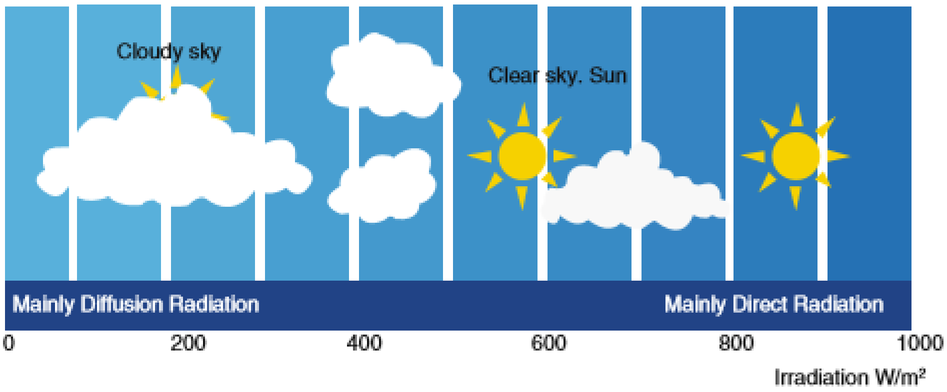


Figure 2.3 Solar Irradiation

Direct or beam radiation is the solar radiation that travels down to the surface of the earth on a straight line without any atmospheric losses due to scattering or absorption.

Diffuse radiation is the solar radiation which reaches the surface of the earth after being scattered or absorbed by molecules in the atmosphere.

Global Horizontal Irradiation (GHI) is the total of direct horizontal irradiation (DHI) and diffuse horizontal irradiation (DIF).

2.1.3.2 Insolation Variations

Insolation varies widely depending on location (and time of year) and when designing a system, it is very important to consider the solar radiation characteristics for the specific location where the solar array will be installed. For instance, a solar array powering a household in a German city would have to be significantly larger than a solar array powering a household with the same energy consumption in the Australian desert. Locations far from the equator such as Poland receive a large amount of irradiation during long summer days but very little during winter when the days are very short.

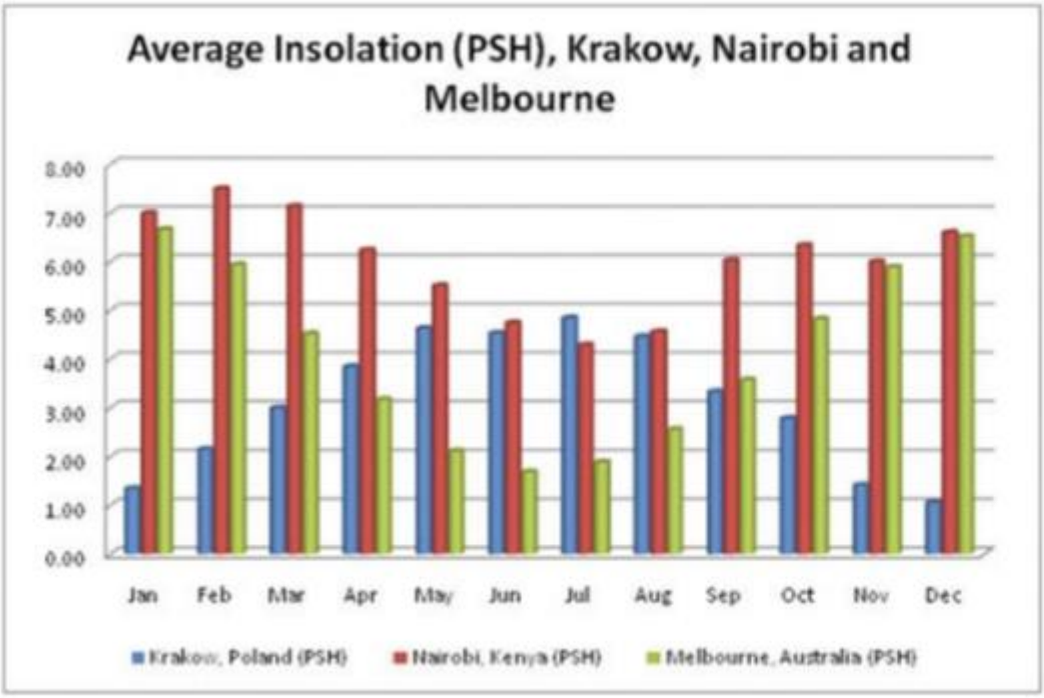


Figure 2.4 Average Insolation (PSH), Krakow, Nairobi and Melbourne

Solar radiation data is often available from the national meteorological bureau or may be supplied by the solar module supplier. NASA provides web data for most of the world and the European Commission Joint Research Centre provides a free web tool, Photovoltaic Geographical Information System (PVGIS), that estimates the daily output of a solar array in any location in Europe or Africa.

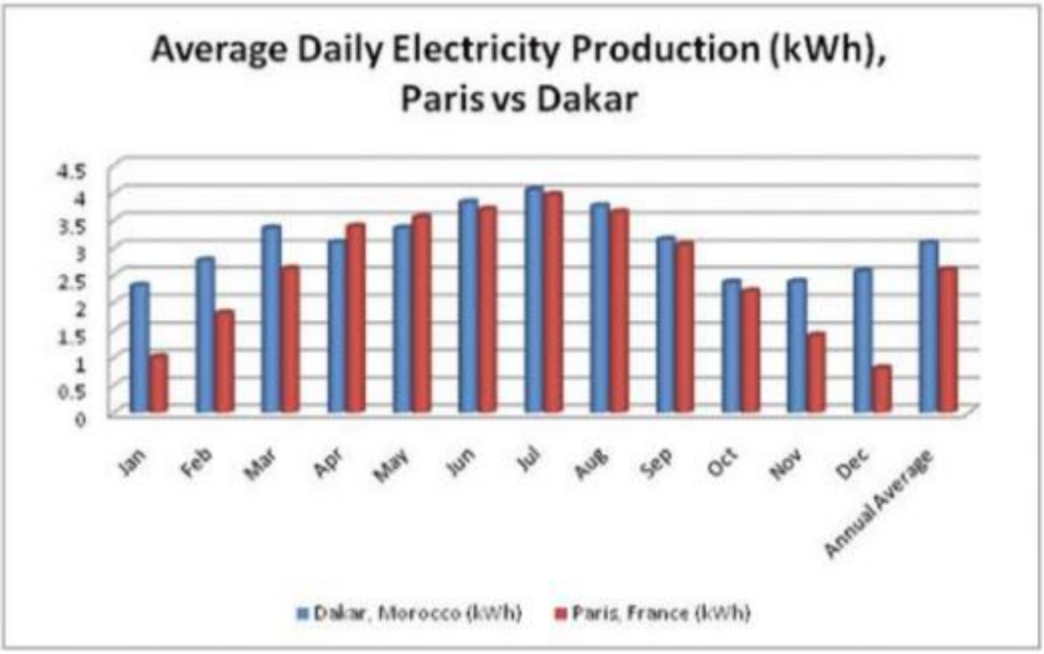


Figure 2.5 Average daily electricity production (kWh)

2.1.3.3 Declination angle, δ

The solar declination angle is the angular position of the sun at solar noon with respect to the plane of the equator, with north positive (-23.45° ≤ δ ≤ 23.45°) (Duffie & Beckman, 2006)

Solar declination is zero at equinoxes and ± 23.45° at solstices. The solar declination angle is given by the Cooper's equation:

$$\delta = 23.45\sin\left(\frac{360(284+n)}{365}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{[1]}$$

Where n is the day number of year i.e., n=1 for January 1, n=344 for December 10, etc.).

2.1.3.4 Solar hour angle, ω

The solar hour angle is the angular displacement of the sun east or west of the local meridian due to the earth's rotation on its axis at 15 degrees per hour; morning negative, afternoon positive (Duffie & Beckman, 2006).It describes the difference between local solar time of the day when the rays of the sun are perpendicularly directed to a given line of longitude. The solar hour angle is given by the equation:

$$\omega = 15\{t - 12\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[2]}$$

Where t is the solar time

2.1.3.5 Sunset and sunrise angle

The sunset hour angle corresponds to the time when the sun sets and it is useful in the solar energy yield analysis. It can be derived from the equation:

$cos\ \omega_s = -tan\phi tan\delta$ ……….. [3]

Where ϕ is the latitude of the site

The sunrise hour angle is the angle which corresponds to the time when the sun rises. Assuming there is symmetry between the time of sunrise and sunset, the sunrise hour angle is given by:

$\omega_r = -\omega_s$ ……………….. [4]

2.1.3.6 Tilt angle, β

Tilt angle is the angle between the plane of the solar panel and the horizontal. Solar PV collectors can either be fixed optimum tilt or manually adjustable tilt depending with the system design. For example, the optimum tilt in Zimbabwe is given by:

$\beta = |\phi| + 5^{o}$ …………. [5]

2.1.3.7 Surface azimuth angle

Surface azimuth angle is the deviation of the projection on a horizontal plane of the normal to the surface from local meridian with zero due North, East positive and West negative.

$\mathbf{-180 \leq \gamma \leq 180}$

2.1.3.8 Angle of Incidence, θ_i

Angle of incidence is the angle between the sun's direct rays (beam radiation) on a surface and the normal to that surface. The diagram below is showing the incident beam radiation on a tilted surface. Figure below shows the orientation of the tilt angle, altitude angle and the angle of incidence.

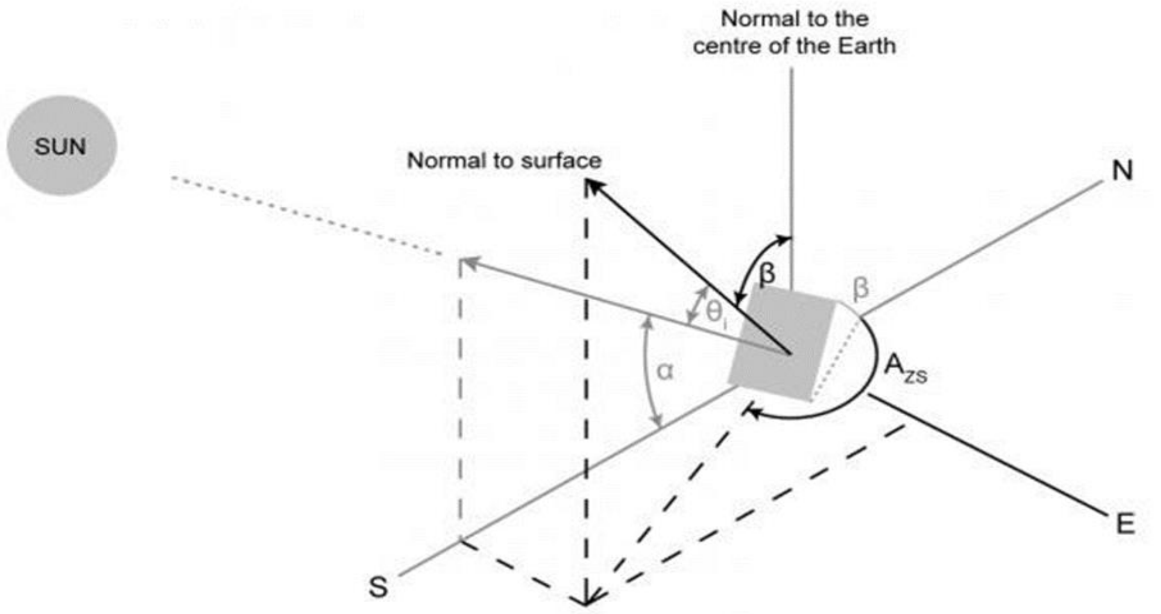


Figure 2.6: Solar angles

$cos\theta i = sin\delta sin\varphi cos\beta - sin\delta cos\varphi cos\gamma + cos\delta cos\varphi cos\omega + cos\delta sin\varphi sin\beta cos\gamma cos\omega +$

$cos\delta sin\beta sin\gamma sin\omega$ .... [6]

2.1.3.9 Solar altitude angle

It is the angle between the line to the sun and the horizontal. This angle is useful in the shading analysis.

2.1.3.9.1 Solar azimuth angle

It describes the position of the sun in the sky, relative to the observer on earth. The solar azimuth angle is the angular position from the south of the projection of beam radiation on a horizontal plane, with east of south positive and west of north negative. The range for the solar azimuth angle is $-180 \leq \boldsymbol{\gamma_s} \leq 180^{\circ}$ and it is calculated from the equation below:

$$\gamma_s = -\left(C_1 C_2 C_3 \gamma'_s + C_3 \left(\frac{1-C_1C_2}{2}\right) 180\right) \text{ .... [7]}$$

Where $\gamma_s = \frac{sin\omega cos\delta}{sin\theta_z}$

$$C_1 \quad = 1 \; if \; |\omega| < \omega_{EW}$$

$$= -1 \;\; otherwise$$

$$C_2 \quad = 1 \; if \; \varphi(\varphi - \delta) \geq 0$$

$$= -1 \; otherwise$$

$$C_3 \quad = 1 \; if \; \omega < 0$$

$$= -1 \;\; otherwise$$

$$cos\omega_{EW} = \frac{tan\delta}{tan\varphi}$$

And the rest of the symbols have their usual meanings.

2.1.4 Geometry for installing solar arrays

The position of a solar module is referred to as its orientation. This orientation of the solar array is very important as it affects the amount of sunlight hitting the array and hence the amount of power produced. The orientation generally includes the direction the solar module is facing (i.e. due south) and the tilt angle, which is the angle between the base of the solar module and the horizontal. The amount of sunlight hitting the array also varies with the time of day because of the sun’s movement across the sky. It then becomes apparent that if the sun is overhead and the solar panel is laid flat on the ground, it will capture all the sun’s rays, as shown in the image below.

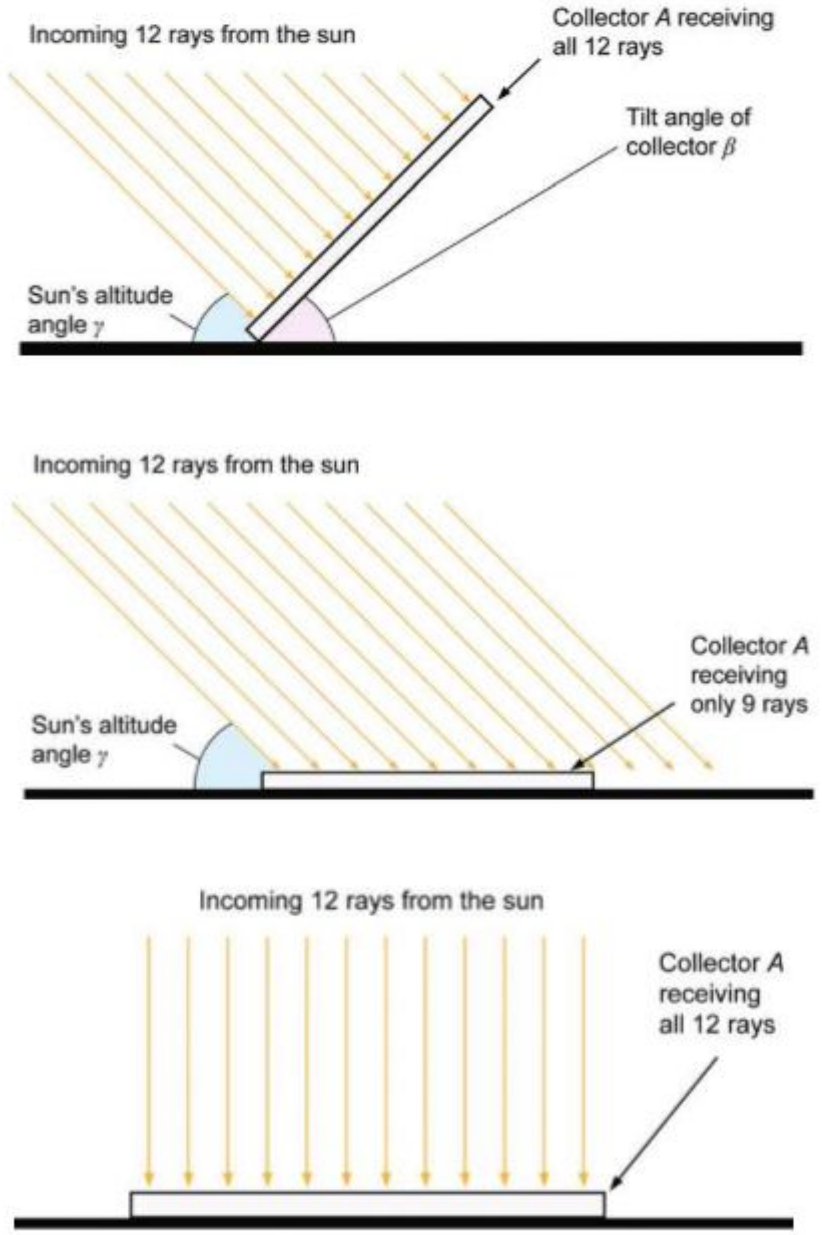


Figure 2.7 Tilt Angle

Solar modules should be installed so that as much radiation as possible is collected. To achieve this, the solar modules should be installed facing either true south (northern hemisphere location) or true north (southern hemisphere location). There will be some exceptions for installation depending on the local environment (i.e. array's installed in a valley in the southern hemisphere may not necessarily face north). To point a module directly towards the sun at all times would require a solar tracking frame to be installed. This can be expensive, so it is not common practice for most PV applications.

2.1.4.1 PRINCIPLE OF PHOTOVOLTAIC SYSTEMS

Photovoltaic systems employ semiconductor cells, usually several square centimeters in size. Semiconductors have four electrons in the outer shell, on average. These electrons are called valence electrons. When the sunlight hits the photovoltaic cells, part of the energy is absorbed into the semiconductor. When that happens the energy loosens the electrons which allow them to flow freely. The flows of these electrons are a current and when you put metal on the top and bottom of the photovoltaic cells. We can draw that current to use it externally, as shown below.

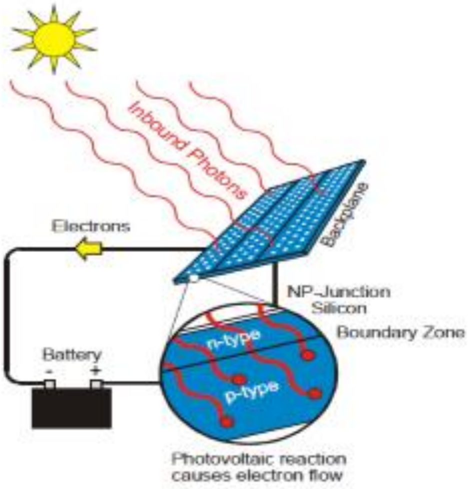


Figure 2.8 Principle of photovoltaic effect

Many cells are collected in a module to generate required power. When many such cells are connected in series and parallel combinations we get a solar PV module, the current rating of the modules depends on the area of the individual cells. For obtaining higher power output the solar PV modules are connected in series and parallel combinations forming solar PV arrays.

2.1.4.2 Series and parallel connections in PV modules

If we make a solar module out of an ensemble of solar cells, we can connect the solar cells in different ways: first, we can connect them in a series connection as shown in (a). In a series connection the voltages add up. For example, if the open circuit voltage of one cell is equal to 0.6 V, a string of three cells will deliver an open circuit voltage of 1.8 V. For solar cells with a classical front metal grid, a series connection can be established by connecting the bus bars at the front side with the back contact of the neighboring cell, as illustrated (b). For series connected cells, the current does not add up but is determined by the photocurrent in each solar cell. Hence, the total current in a string of solar cells is equal to the current generated by one single solar cell.

Figure (d) shows the I-V curve of solar cells connected in series. If we connect two solar cells in series, the voltages add up while the current stays the same. The resulting open circuit voltage is two times that of the single cell. If we connect three solar cells in series, the open circuit voltage becomes three times as large, whereas the current still is that of one single solar cell.

Secondly, we can connect solar cells in parallel as illustrated in (c), which shows three solar cells connected in parallel. If cells are connected in parallel, the voltage is the same over all solar cells, while the currents of the solar cells add up. If we connect e.g. three cells in parallel, the current becomes three times as large, while the voltage is the same as for a single cell, as illustrated in (d).

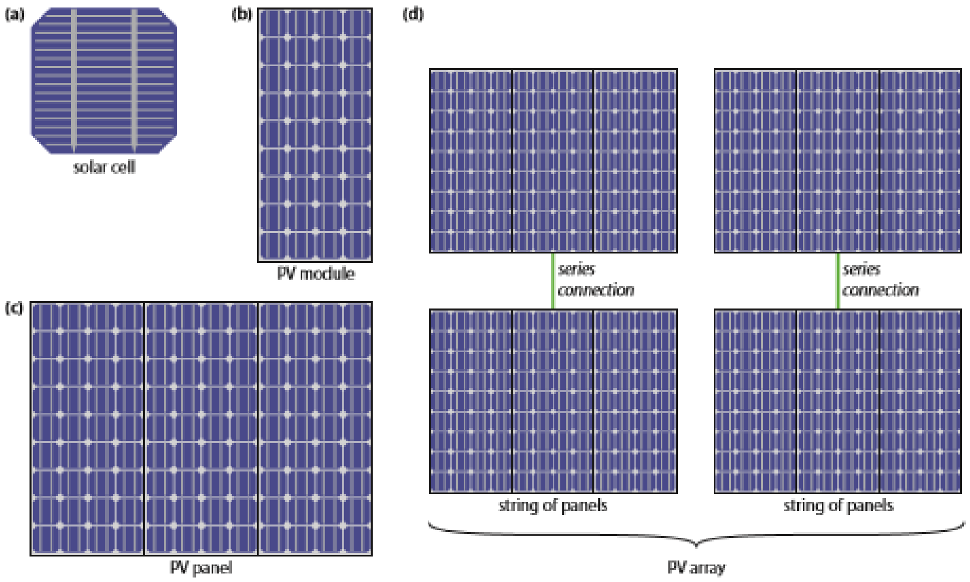


Figure 2.9: Illustrating (a) a solar cell, (b) a PV module, (c) a solar panel, and (d) a PV array.

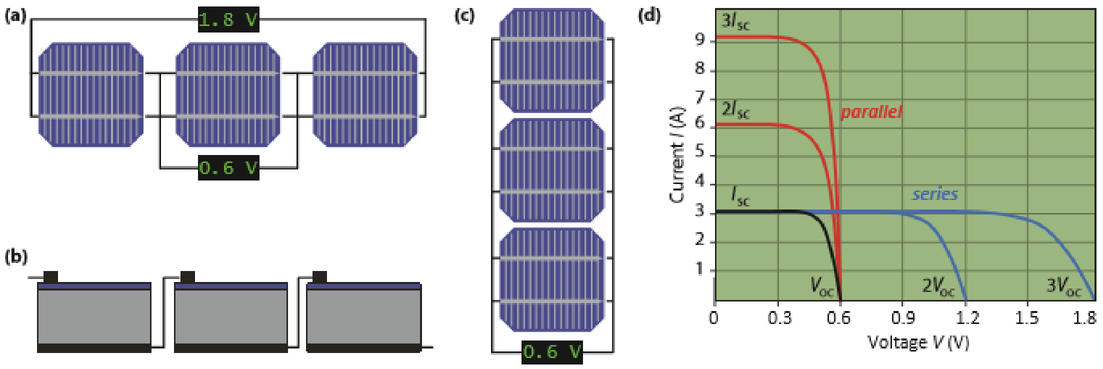


Figure 2.10: Illustrating (a) a series connection of three solar cells and (b) realization of such a series connection for cells with a classical front metal grid. (c) Illustrating a parallel connection of three solar cells. (d) I-V curves of solar cells connected in series and parallel.

2.1.5 TYPES OF PV CELLS

2.1.5.1 SOLAR PHOTOVOLTAIC FLAT PLATE COLLECTORS

Photovoltaic flat plate collectors change solar radiation incident on them straight to DC electrical energy. These collectors are made from silicon and are sub divided into three categories which are mono-crystalline, polycrystalline and thin film photovoltaic modules. The purity of the silicon used differentiate the three types of modules and the highly pure silicon based modules are the most expensive and efficient.

2.1.5.2 Mono-crystalline modules

Monocrystalline modules comprise of solar cells which are made out of silicon ingots, cylindrical in shape. These solar panels have the highest efficiency rates since they are made out of the highest-grade silicon (Maehlum, 2015). Monocrystalline silicon solar panels are space-efficient. However, the disadvantages of Monocrystalline panels are that if the solar panel is partially covered with shade, dirt or snow, the entire circuit can break down. They are also expensive hence not quite suitable for large scale solar power plants.

Figure 2.11: Monocrystalline module

2.1.5.3 Polycrystalline modules

Polycrystalline silicon solar cells are made by melting and pouring raw silicon is into a square mold, which is cooled and cut into perfectly square wafers (Maehlum, 2015) . The amount of waste silicon used in these panels is less as compared to those in monocrystalline modules. The process used to make polycrystalline silicon is simpler and this is why polycrystalline silicon solar panels cost less, which makes them suitable for large scale solar PV plants and rural electrification. A typical polycrystalline module is shown below

Figure 2.12: Polycrystalline module

2.1.5.4 Thin Film modules

Thin film solar cells are made by depositing one or several layers of the photovoltaic material onto a substrate. Depending on the type of substrate, the thin film modules can be amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and organic photovoltaic cells (OPC). These have the lowest efficiency range (7- 13%) because of the lower level of purity of the silicon used in their production. Higher temperatures have less impact on the performance of the cell and they cost less compared to the mono-Si and p-Si modules. However, thin film modules tend to degrade at a faster rate as compared to the other two technologies.

Figure 2.13: Thin film modules

2.1.6 Selection of the type of module

Table 2.1 below shows the comparison of the different module technologies. The data was adapted from the El Salvador Report (2012), a case study for a 20MW plant in El Salvador.

Description	Thin Film	Thin Film	Crystalline	Crystalline
Module technology	Amorphous Silicon a-Si	Cadmium Telluride CdTe	Monocrystalline	Polycrystalline
Total number of modules/MW	10 020	12 528	4 008	4 008
Module area/MW in m^2	14 329	9 020	6 447	6 447
Total Area in ha	1.9-3.1	1.3-2.2	0.8-1.5	0.8-1.5
Max Power /ha in MW	0.5	0.75	1.25	1.25
Yield/Year in kWh/kW	1.528	1.528	1.419	1.420
Performance ratio	79.8%	79.8%	74.1%	74.2%
Module efficiency	7-13%	7-13%	15-20%	15-16%
Price in US$/kW	2 566-2 901	2 566-2 901	2 789-3 124	2 566-2 901

Table 2.1: Comparison of Thin Film, monocrystalline and polycrystalline modules from the El Salvador Report (2012)

The selection of the module was done considering the costs, efficiencies, space efficiency and lifespan of the modules. The extract above was taken from a report on the Case Study of a 20MW PV Power Plant in El Salvador by iLF Consulting Engineers (Anon., 2012).From the table, polycrystalline modules are the least expensive of the 3 modules(CdTe, monocrystalline & polycrystalline).It has slightly higher yield/year than the monocrystalline module. According to Jintech Solar Product Guide (2013), polycrystalline modules has also the least cost for the same lifespan of 25 – 30 years. Therefore, the polycrystalline module is the cost effective option for solar PV power generation on a large scale.

2.1.6.1 Photovoltaic system types

Photovoltaic systems can be generally divided into two basic groups:

1. Photovoltaic systems not connected to the network, stand-alone systems (off-grid)
2. Photovoltaic systems connected to public electricity network (on-grid)

There are lots of different subtypes of photovoltaic systems according to type and method of connecting to the network, or a way of storing energy on independent systems.

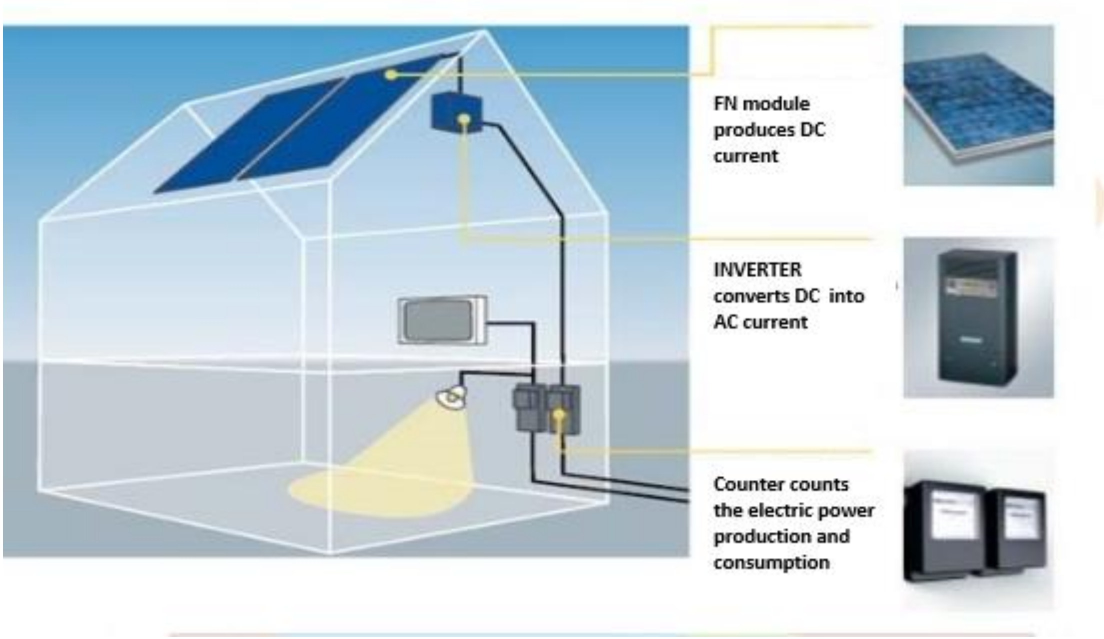


Figure 2.14 Network-connected photovoltaic system

The main components of PV systems are photovoltaic modules, photovoltaic inverter, mounting sub frame and measuring cabinet with protective equipment and installation.

Photovoltaic modules convert solar energy into DC current, while photovoltaic inverter adjusts the produced energy in a form which can be submitted to the public grid. The AC voltage is supplied to the electricity network through the protection and measuring equipment.

Photovoltaic inverter is usually located indoors, although there are inverters for outdoor installation, where it must not be directly exposed to sunlight. Inverters produce high-quality AC current of corresponding voltage and are suitable for a network connected photovoltaic systems. Network inverters operate like any other inverter, with the difference that the network inverters must ensure that the voltage they supply is in phase with the network voltage. This allows the photovoltaic systems to deliver the electricity to the electrical network.

Electrical connection is usually located in the electrical control box, which is located in a separate room, but can also be placed in the measurement and terminal box, which then connects to the electrical control box. The meter is installed at the point of connection, a single phase, two-tariff, electronic system for single-phase, and a three phase, two tariff, electronic system for two-phase and three phase systems.

In such installations it isregularly proposed to setting up a fuse in front of and behind the counters in order to permit replacement of the meter at a no load condition. The exact conditions of connection are synchronized with the local distributor of electric energy - HEP ODS. Power OFF buttons must be provided both on the side of photovoltaic modules as well as on the side of network connection.

The output voltage of the inverter must be in accordance with the Regulation on standardized voltages for low voltage electricity distribution network and electrical equipment. Standard sizes of the nominal voltage is 230V, up to 400V between phase and neutral conductor, between phase conductors, the quadphase network nominal frequency of 50 Hz and under normal conditions, it should not differ from the nominal value by more than ± 10%.

Due to the large exposures to lightning, besides being connected to the lightning protection installation, the photovoltaic modules are protected by arresters and bias as well. Arresters are installed immediately after the module in order to prevent the impact of bias on the installation of the building.

2.1.6.2 Network-connected home system (possibility for own consumption)

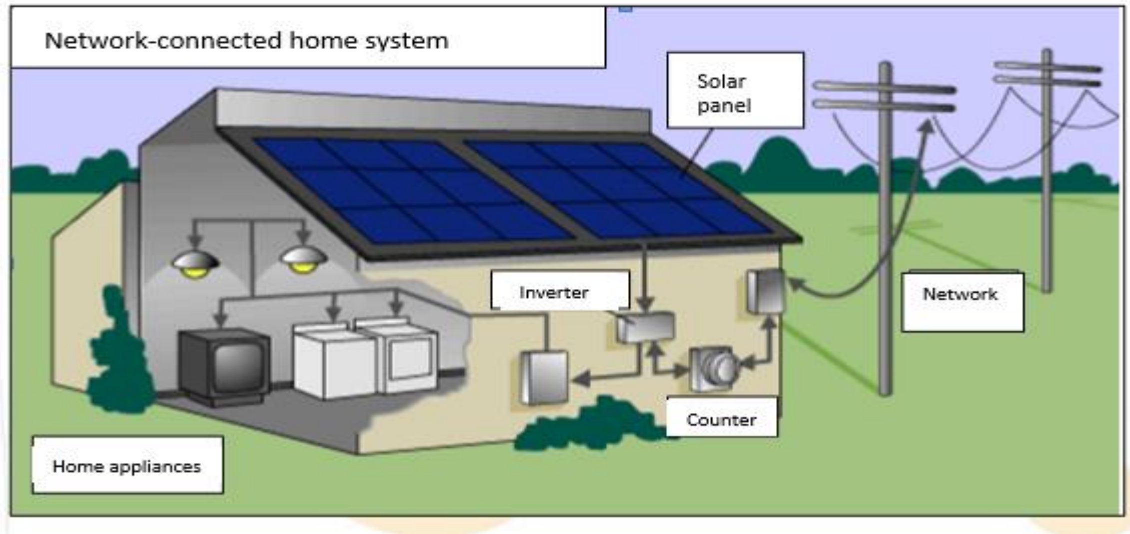


Figure 2.15 Network-connected home photovoltaic system

These are the most popular types of solar photovoltaic systems that are suitable for home and commercial installations in developed and urban areas. Connection to the local electricity network allows selling to the local distributor of electric energy any excess of electricity generated and not used in the household consumption, because the PV system is connected to the network via a home installation in parallel operation with the distribution system. Also, the home is supplied with electricity from the grid when there is no sunny weather. The inverter, as already discussed, is used to convert direct current (DC) produced by the photovoltaic modules into alternating current (AC) located in the electrical grid and used to drive all the household appliances. This system gives two choices to the user: to sell the entire electricity produced to the local distributor, delivering all the electricity in the network (especially if there is a price incentive for electricity produced from renewable sources according to the status of eligible producer of electric energy - feeding tariffs) or the electricity produced can be used to meet the current needs of households and sell any surplus in the electricity grid.

2.1.6.3 Network-connected solar power plants (farms)

Figure 2.16 Solar farm

These systems, also connected to the network, are generating large amounts of electricity by a photovoltaic installation on a localized area. The power of such photovoltaic power ranges from several hundred kilowatts to tens of megawatts, recently up to several hundred megawatts. Some of these installations can be located on large industrial facilities and terminals, but more often on large barren land surfaces. Such large installations are exploiting existing facilities to produce electricity at the location and thus compensate part of the electric energy demand in the area.

To have a feeling of size, talking about solar farms, it is worth to mention an example of a large-scale solar farm in the former military airport in Germany: 40 MWp power, thin film technology, surface area 110 hectares, which is equivalent to an area of 200 football stadiums, the expected annual production of 40 million kWh of electricity, saving 25.000 tonnes of CO2, and cost about 130 million €.

2.1.6.4 Stand-alone systems (off-grid) or isolated systems

These systems are used in rural areas where there is no electricity network and infrastructure. The systems are connected to a reservoir of energy (battery) by a control over the filling and emptying. The inverter can also be used to provide alternating current for standard electrical equipment and appliances.

Figure 2.17 Standalone photovoltaic system

Typical standalone photovoltaic installations are used to ensure the availability of electricity in remote areas (mountain resorts, islands, rural areas in the developing areas). Rural electrification means either small home solar photovoltaic installations covering basic electricity needs of an individual household, or bigger solar photovoltaic network that provides enough electricity for several households.

2.1.6.5 Hybrid systems

A solar photovoltaic system can be combined with other energy sources, such as biomass

generator, wind turbines, diesel generator, all to ensure a constant and sufficient supply of electricity, since it is known that all renewable energy sources, including photovoltaic systems, are not constant in energy production. It means that, when there is no sun, the system does not produce electricity, although the need for energy is constant, and therefore must be met from other sources. The hybrid system can be connected to a network, standalone or as a support network.

2.2 Partial shading and by pass diodes

PV modules have so-called bypass diodes integrated. To understand the reason for using such diodes, we have to consider modules in real-life conditions, where they can be partially shaded, as illustrated in Figure 2.18(a). The shade can be from an object nearby, like a tree, a chimney or a neighboring building. It also can be caused by a leaf that has fallen from a tree. Partial shading can have significant consequences for the output of the solar module. To understand this, we consider the situation in which one solar cell in the module shaded for a large part shaded. For simplicity, we assume that all six cells are connected in series. This means that the current generated in the shaded cell is significantly reduced. In a series connection the current is limited by the cell that generates the lowest current, this cell thus dictates the maximum current flowing through the module.

In Figure 2.18(b) the theoretical I-V curve of the five unshaded solar cells and the shaded solar cell is shown. If the cells are connected to a constant load R, the voltage across the module is dropping due to the lower current generated. However, since the five unshaded solar cells are forced to produce high voltages, they act like a reverse bias source on the shaded solar cell. The dashed line in Figure 2.18 (b) represents the reverse bias load put on the shaded cell, which is the I-V curve of the five cells, reflected across the vertical axis equal to 0 V. Hence, the shaded solar cell does not generate energy, but starts to dissipate energy and heats up. The temperature can increase to such a critical level, that the encapsulation material cracks, or other materials wear out. Further, high temperatures generally lead to a decrease of the PV output as well.

These problems occurring from partial shading can be prevented by including bypass diodes in the module, as illustrated in Figure 2.18 (c), a diode blocks the current when it is under negative voltage, but conducts a current when it is under positive voltage. If no cell is shaded, no current is flowing through the bypass diodes. However, if one cell is (partially) shaded, the bypass diode starts to pass current through because of the biasing from the other cells. As a result current can flow around the shaded cell and the module can still produce the current equal to that of a unshaded single solar cell. For cells that are connected in parallel, partial shading is less of a problem, because the currents generated in the others cells do not need to travel through the shaded cell. However, a module consisting of 36 cells in parallel have very high currents (above 100 A) combined with a very low voltage (approx. 0.6 V). This combination would lead to very high resistive losses in the cables; further an inverter that has only 0.6 V as input will not be very efficient. Therefore, combining the cells in series and using bypass diodes is much better an option to do.

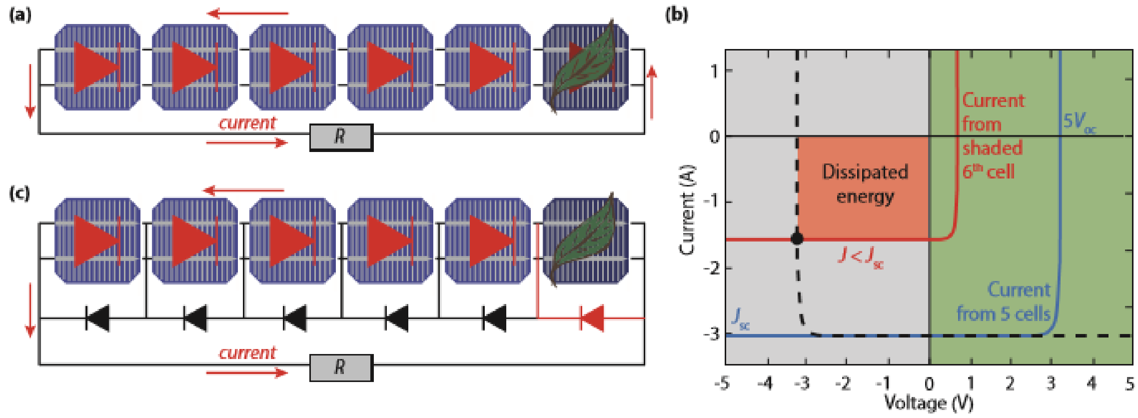


Figure 2.18: Illustrating (a) string of six solar cells of which one is partially shaded, which (b) has dramatic effects on the I-V curve of this string. (c) Bypass diodes can solve the problem of partial shading.

2.2.1 ADVANTAGES OF PV SYSTEMS

PV systems are considered static electricity generators as they create electricity directly from sunlight. They come prepackaged, ready to be mounted and wired. Modules contain no moving parts, eliminating service and maintenance needs.

- PV systems come in a range of sizes and output suitable for different applications. They are lightweight, allowing for easy and safe transportation.
- PV system can be easily expanded by adding more modules either in series to expand the system's voltage or in parallel to enlarge the current.
- PV systems are manufactured to withstand the most rugged conditions. Modules are designed to endure extreme temperatures, at any elevation, in high winds, and with any degree of moisture or salt in the atmosphere. Systems can be designed with storage capabilities to provide consistent, high-quality power even when the sun isn't shining.
- PV systems cause no noise or carbon emissions i.e. no pollution.

2.2.2 The drawbacks of photovoltaic systems are:

- Very high manufacturing cost compared to other renewable resources.
- Maximum power point problems.
- Requires regular cleaning of its outer surfaces from dust.
- Significantly low in efficiency.

2.3 Conclusion

In this chapter, an overview of photovoltaic technology, and photovoltaic background and principle of photovoltaic systems are presented. The photovoltaic energy in particular is reviewed with cell type. The Solar geometry, position of the sun and the variations of insolation in different areas with different climatic conditions. The different connections of the solar cells have been reviewed and the effect on the output power for each connection type. The chapter also gives an account of the advantages and disadvantages of photovoltaic technology in general.

CHAPTER 3:

Modelling and System Topology of Photovoltaic Technology

3.1 Introduction

PV systems connected to the grid have an important role in distributed generation systems. In order to keep up with the current trends regarding the increase in PV installations, PV inverters should have the following characteristics: Low cost, small weight and size, due to residential installations, high reliability to match with that of PV panels, high efficiency and be safe for human interaction.

This chapter highlights the System Description and Modelling of the Photovoltaic System connected to the grid. Furthermore, a summary of several PV inverter topologies is presented, followed by discussions about a boost converter with a controller for the maximum power point, which is used to track the MPP of the PV. This topology allows studying the efficiency of the maximum power point control method and the performance of the PV to achieve the maximum power at different temperature and irradiance.

3.2 MODELISATION OF A PV CELL

PV cell is a semiconductor p-n intersection that transforms sunlight to electrical power. To model a solar cell, it is imperative that we asses the effect of different factors on the solar panels and to consider the characteristics given by the manufacturers in the datasheet. It is to be noted that to form a PV module, a set of cells are connected in series or in parallel. To form a PV array, a set of PV modules are connected in series and in parallel. Thus, the mathematical models for PV array are attained while utilizing the basic description equivalent circuit of the PV cells. A PV cell is usually embodied by an electrical equivalent of one-diode, resistance series **Rs** and resistance parallel **Rp** as shown below.

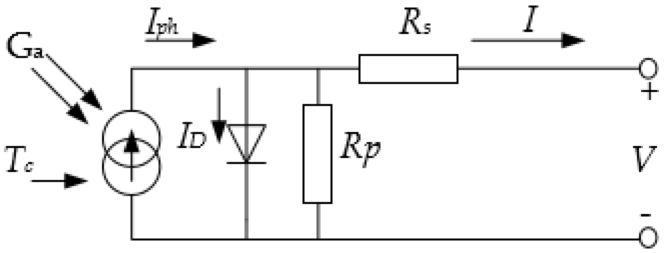


Figure 3.1 Model of a PV cell

From the figure, the different parameters characteristics of the PV cells are:

Iph: currents generated by the solar cells (A)

Rs: resistance series (Ω)

Rp: resistance parallel (Ω)

Ga: irradiance from the sunlight (W/m2)

T: cell temperature (K)

Id: diode current (A)

I: output current of the PV (A)

V: output voltage of the PV (V)

Manufacturer of the solar module gives the another parameter needed to model the solar cells. The datasheet which gives the electrical characteristics is calculated under standard test condition STC when the temperature T is 25°C and the irradiance G is 1000 W/m2. The parameters that can be found inside the datasheet are:

Voc: open circuit voltage (V)

Isc: short-circuit current (A)

Pmp: power at maximum power point,

Vmp: voltage at maximum power point

Imp: current at maximum power point

The solar cell is modelled first, then extends the model to a PV module, and finally

models the PV array.

the output current of the PV cell is

$$I = I_{ph} - I_d$$

where

I_{ph}: photon produced by the cell,

I_d: diode current

By Shockley equation, the diode current I_d is given by

$$I_d = I_0\left(e^{qV_d/kT} - 1\right)$$

where

I0: reverse saturation current of diode,

q: elementary electron charge (1.602x10-19 C),

Vd: diode voltage,

k: Boltzmann constant 1.381x10-23 (J/K)

T: temperature in kelvin (K)

The relation between voltage and current result by replacing the diode current

$$I = I_{ph} - I_0\left(e^{qV_d/kT} - 1\right)$$

where Vd is the output voltage of the PV cell. The reverse saturation I0 is found by using the above equation. By setting the current I equal to zero and calculating at temperature T1

$$I_0(T_1) = \frac{I_{ph}(T_1)}{\left(e^{qV_{oc}/kT} - 1\right)}$$

The current generated by the solar cells Iph can be approximated with the short circuit current Isc. The current generated can be calculated for other irradiance. The standard current, temperature and irradiance from the datasheet are used to determine the current at different condition.

$$I_{sc} \approx I_{ph}$$

$$I_{sc}(T_1) = \left(\frac{G}{G_{nom}}\right) I_{sc}\left(T_{1,nom}\right)$$

where

$I_{sc(T1)}$: current at temperature T_1

$T_{1,nom}$ the temperature of cell from datasheet at STC

G_{nom}: irradiance from datasheet at STC

After calculation, [3] gives the equation of the PV

$$I = I_{ph} - I_0\left[e^{q\left(\frac{V+I.R_s}{akT}\right)}\right] - \left(\frac{V + I.R_s}{R_p}\right)$$

where

a: diode quality factor between 1 and 2 and must be estimated. The value of "**a**" is equal to 1 for ideal diode. V is the cell voltage. For a PV module, the cell voltage is multiplied by the total amount of the cells found within the series. The reverse saturation current I0 depends on the temperature T. It is calculated by the following equation

$$I_0 = I_0(T_1)\left(\frac{T}{T_1}\right)^{\frac{3}{n}} . e^{\frac{qV_g(T_1)}{ak\left(\frac{1}{T}-\frac{1}{T_1}\right)}}$$

The value of resistance series **Rs** is quantified from the slope **dV/dI** of the I-V curve at the point open circuit voltage. The equation **Rs** is given by

$$R_s = -\frac{dV}{dI} - \frac{akT/q}{I_0 . e^{\left(\frac{qV_{oc}}{akT}\right)}}$$

The model is completed by using the following recursive equations to find the currents. The recursive equation is used to calculate the current for a PV cell. It is more convenient to solve numerically. The equation introduces a simplified method to calculate resistance series and neglect the resistance parallel.

$$I_{n+1} = I_n - \frac{I_{ph} - I_n - I_0\left[e^{q\left(\frac{V+I_n.R_s}{akT}\right)} - 1\right]}{-1 - I_0\left(\frac{q.R_s}{akT}\right)e^{q\left(\frac{V+I_n.R_s}{akT}\right)}}$$

3.2.1 INTRODUCTION TO PV CHARACTERISTICS

Figure 3.2 and 3.4 show the current voltage (I-V) characteristics of PV panel. This curve is nonlinear and crucially relies on the temperature along with the solar irradiation. In figure 3.2, when the irradiation increases, the current increases more than the voltage and the power maximum power point **Pmpp** increases as well.

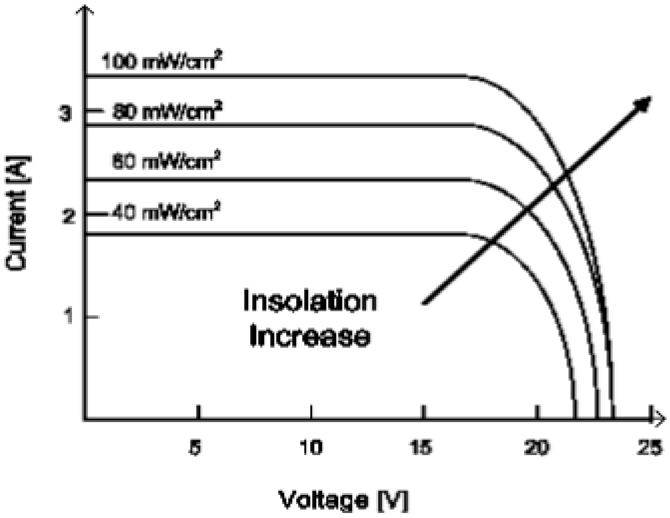


Figure 3.2: I-V Characteristics of the PV as function of irradiance

Figure 3.3 shows the variation of the current with the temperature, the current changes less than the voltage.

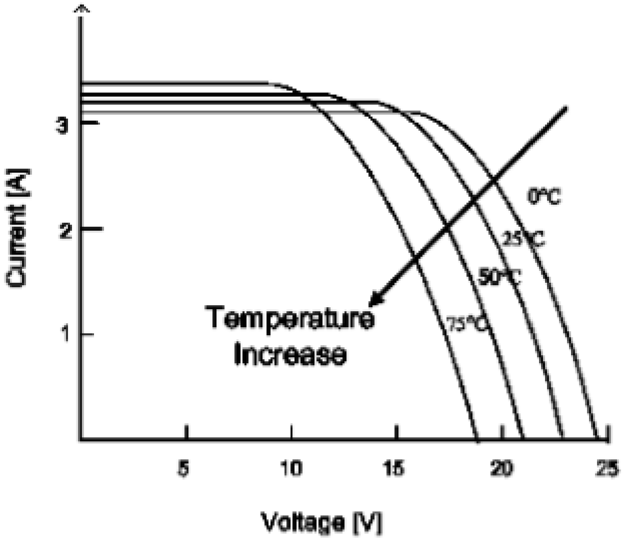


Figure 3.3: I-V Characteristics of the PV as function of Temperature

Thus, a dynamic point exists on the I-V curve called the Maximum power point MPP. The entire PV system has to execute at its maximum output power as shown in figure 3.4 The location of the power point maximal is unknown, for that reason we use calculation models and search algorithms methods to sustain the PV array functioning mark at the MPP.

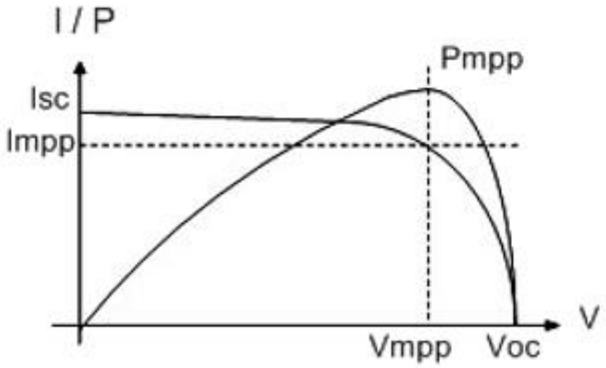


Figure 3.4: I-V curve, P-V curve with the MPP

The effects of series losses, shunt losses and mismatch losses on the I-V curve are represented in Figure 3.5 Non-uniform shading is a mismatch effect.

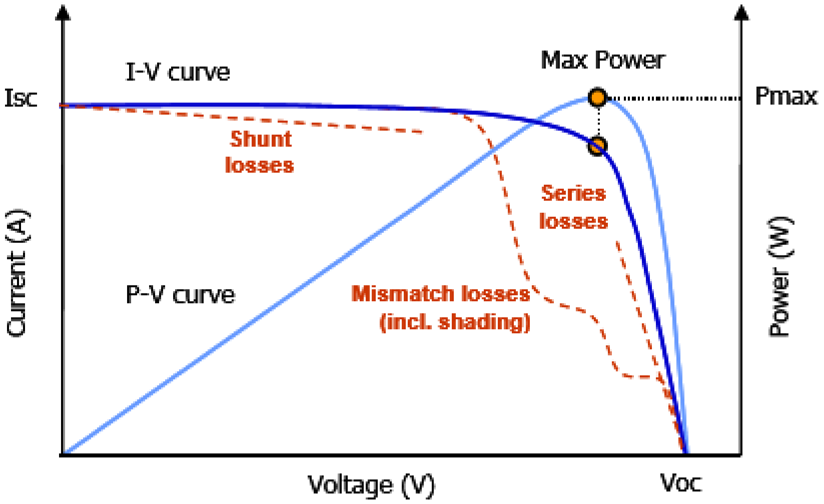


Figure 3.5 Several categories of losses that can reduce PV array output. The I-V curve provides important troubleshooting clues

3.2.2 DC-DC Converter for Solar PV System

Generally, three basic types of converters are accountable as per their use. They either step up by boosting voltage at output known as Boost converter or by stepping down by reducing voltage known as Buck converters. There is another class of converters used for both stepping up or down the voltage output described as Buck-Boost converters. Buck-Boost converters reverse polarity of output voltage, as such they are sometimes known as inverters.

3.2.3 Operation of the boost converter

The main purpose of the DC/DC is to convert the DC input from the PV into a higher DC output. The maximum power point tracker uses the DC/DC converter to adjust the PV voltage at the maximum power point. The boost topology is used for stepping up the low voltage input from the PV. A boost type converter steps up the PV voltage to high voltage necessary for the inverter. Figure 3.6 shows the Boost converter. The DC input voltage is in series with an inductor L that acts as a current source. A switch T is in parallel with the current source that turns on and off periodically, providing energy from the inductor and the source to increase the average output voltage.

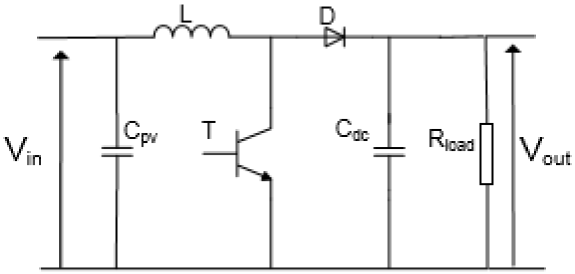


Figure 3.6: Topology of Boost converter

The voltage ratio for a boost converter is derived based on the time integral of the inductor voltage equal to zero over switching period. The voltage ratio is equivalent to the ratio of the switching period to the off time of the switch

$$\frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{1-D}$$

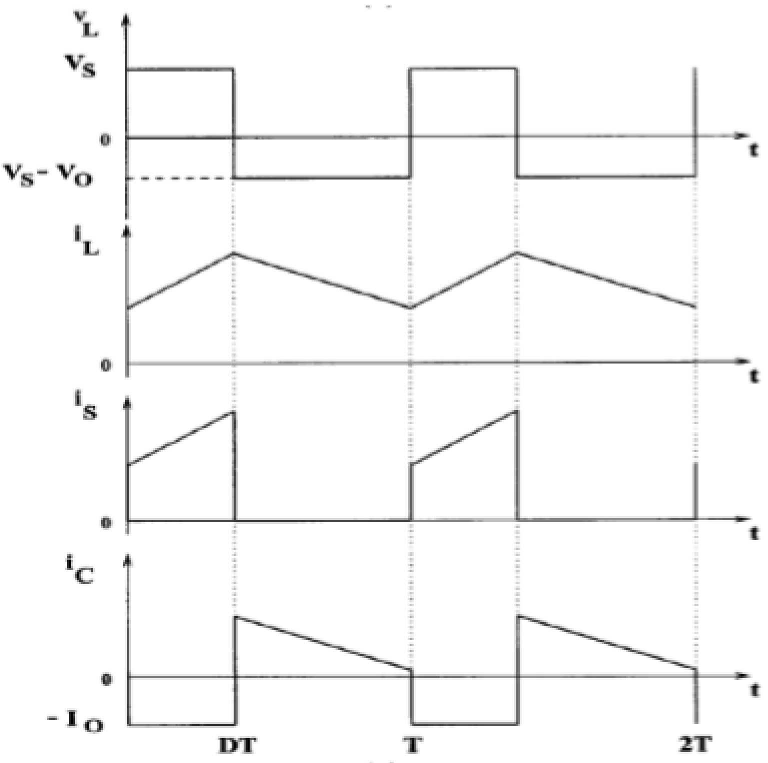


Figure 3.7 shows the different characteristics of boost converters. It shows the source voltage, source current, inductor current, capacitor current with respect to time for a complete duty cycle.

3.3 MAXIMUM POWER POINT TRACKING

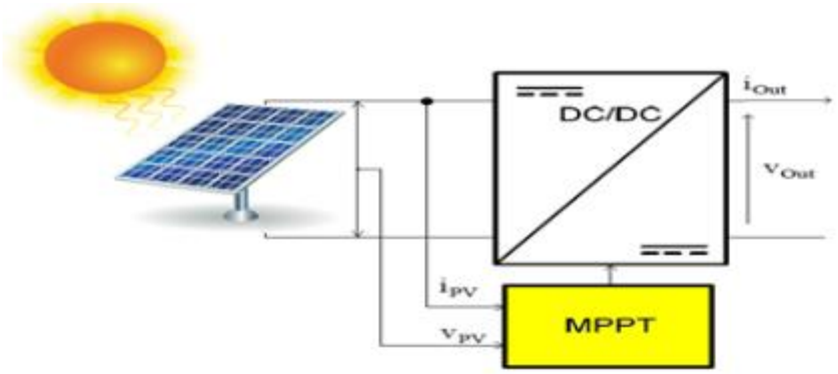


Fig.3.8 Maximum Power Point Tracker (MPPT) system as a block diagram

Maximum power point tracker (MPPT) tracks the new modified maximum power point in its corresponding curve whenever temperature and/or insolation variation occurs. MPPT is used for extracting the maximum power from the solar PV array and transferring that power to the grid. A DC/DC (step up/step down) converter acts as an interface between the inverter and the array. The MPPT changing the duty cycle to keep the transfer power from the solar PV array to the grid at maximum point. The function of the inverter is to convert the output DC voltage of the PV into AC and to keep the output voltage of the DC/DC converter constant. In order to accomplish that, two controllers are required; one for the DC/DC converter, and the other for the inverter.

3.3.1 CONTROL ALGORITHMS

Perturb & Observe Algorithm (P&O) and Incremental Conductance Algorithm (ICT) are mainly used among other methods because mainly of their cost effective and easier to use.

3.3.2 Perturb and Observe method (P&O)

Perturb and Observe is a widely used method. It is common because of the simple feedback structure and the fewer control perimeters. The basic idea is to give a trial increment or decrement in the voltage, and if this result in an increase in the power, the subsequent perturbation is made in the same direction or vice versa. This method is easy enough to handle and manipulate. However, this method of monitoring the perimeter causes a delay and therefore tracking a real time maximum power point is difficult

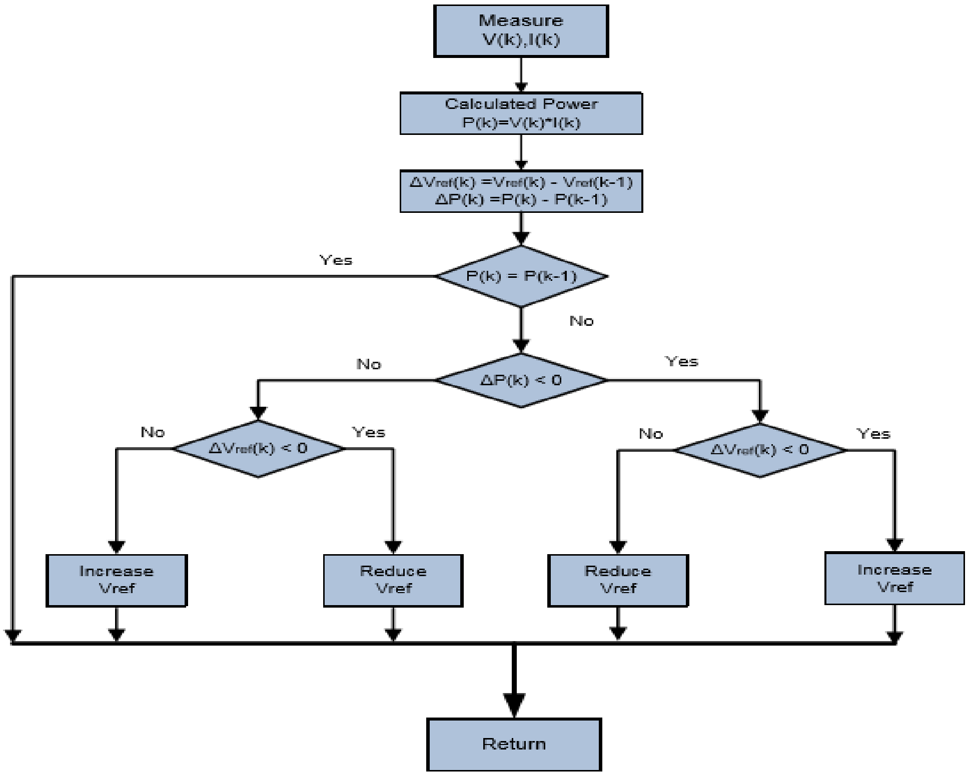


Figure 3.9 Flowchart for maximum power point tracking for (P&O) Algorithm.

3.3.3 Incremental Conductance method (ICT)

The incremental conductance method is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by eq

$$\frac{dP}{dV} = 0 \quad \text{, at MPP}$$

$$\frac{dP}{dV} > 0 \quad \text{, left of MPP}$$

$$\frac{dP}{dV} < 0 \quad \text{, right of MPP}$$

Since,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \approx I + V\frac{\Delta I}{\Delta V}$$

Using these equations, the tracking point is given by

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad \text{, at MPP}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad \text{, left of MPP}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad \text{, right of MPP}$$

The flow chart for maximum power point tracking for Incremental Conductance Algorithm is shown in Fig.3.10

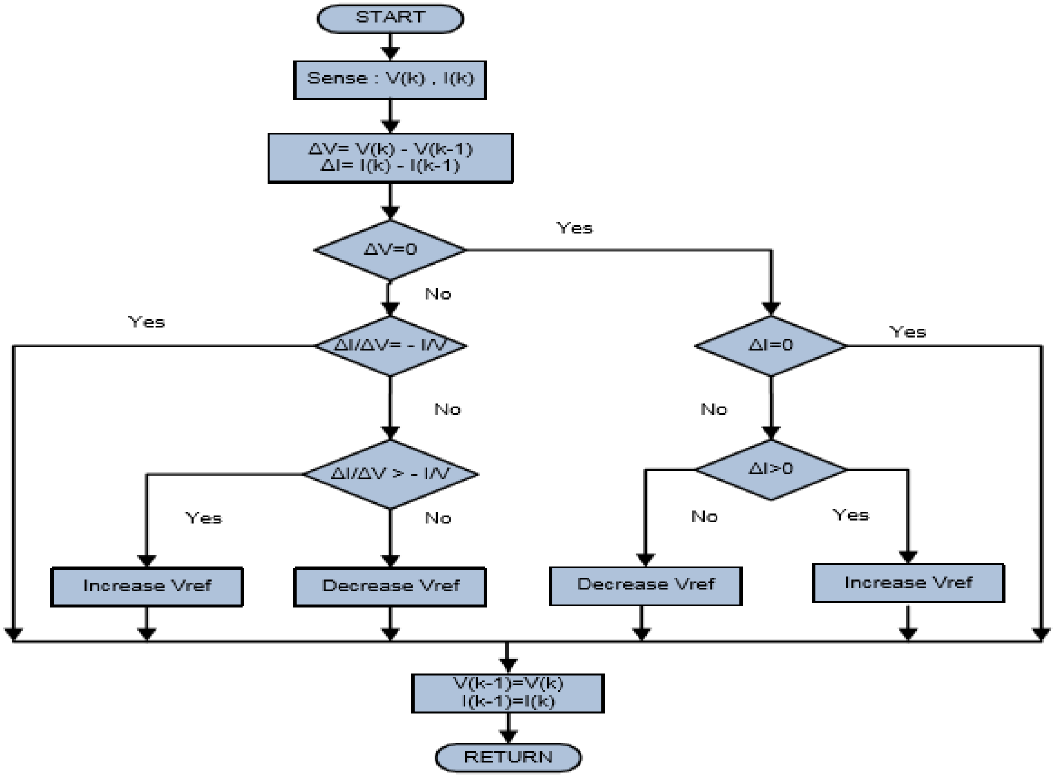


Figure 3.10 Flow Chart for maximum power point tracking for ICT Algorithm.

the MPP can thus be tracked by comparing instantaneous conductance I/V to the incremental conductance ΔI/ΔV as shown in the flow chart in Figure 3.10 The Incremental Conductance Algorithm based tracking adjusts the duty cycle D of boost converter which adjusts the operating voltage of PV array to operate at MPP. It is very unlikely for the ICT algorithm to stop exactly on the MPP. Hence, practical ICT algorithm considers the MPP reached when the operating point is within a certain error margin which is given by equation

$$I + V\frac{\Delta I}{\Delta V} < e$$

This method gives a very good and accurate performance under rapidly varying conditions. However, the drawback is that the actual algorithm is very complicated to handle. It requires sensors to carry out the computations and high power loss through the sensors.

3.4 DC/AC inverter

The function of the DC/AC inverter is presented below. It should mould the current into a waveform i.e. sinusoidal, and subsequently transform the current to ac current with low harmonics content. The PV array is used to inject a sinusoidal current to the grid. The topology adopted depends on the application whether it is a standalone PV system or grid connected. Other criteria such as the power output of the PV, the total current harmonics and the cost could influence the choice of inverter design. In grid connected PV system, the inverters should have island detection, power quality within the standards, grounding, etc. The typical DC/AC inverter could be a line frequency-commutated current source inverter (CSI), a full-bridge three-level, half-bridge diode clamped three-level VSI, etc. line commutated inverters are qualified robust, efficient and cheap but have a power factor between 0.6 and 0.7. Self-commutated inverters are used quite often; they are capable switching at high frequency, which introduce more losses in semiconductor. The self-commutated inverter is robust and cheap technology. line frequency-commutated inverter uses a signal sinusoidal to generate the AC output. The drawbacks with this configuration are the power quality of the harmonics and unnecessary fault situation. The harmonics can cause series resonance with the capacitors installed around the system. The full-bridge inverter is the most used in PV system.

The inverter could be unipolar or bipolar depending on the shape of the output voltage waveform. The drawbacks with bipolar is “two IGBT and two diodes switching at the switching frequency with whole input voltage, therefore doubling the switching losses

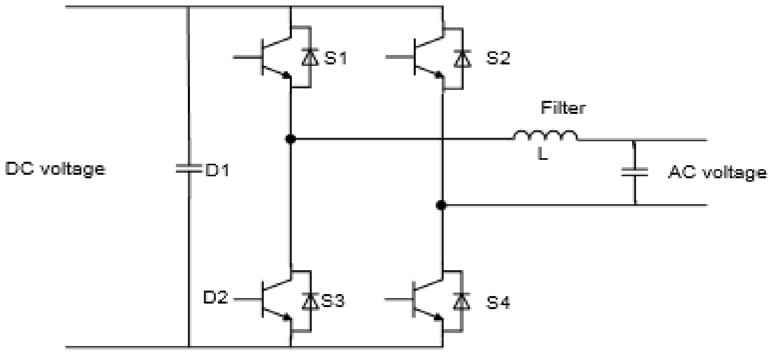


Figure 3.11: Single-phase full bridge inverter

Figure 3.12 is the three-phase full bridge inverter. The command of the switch depends on the modulation schemes to obtain the sinusoidal output.

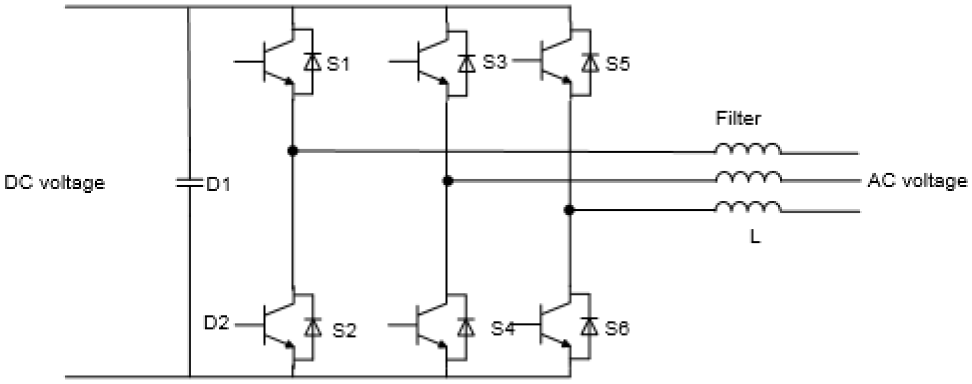


Figure 3.12: Three-phase full bridge inverter

3.4.1 The system topology

The inverter could be a single stage inverter, dual stage inverter. Each topology has their advantages and disadvantages. An optimization is necessary for the choice of topology. The topology should guarantee that the output current is a high quality sine wave and in phase with voltage if grid connected, also with low distortion harmonic. In **figure,** the different topology of the photovoltaic is shown. In **figure a**, the PV array is connected in series and parallel then linked by a singular inverter. A PV string is for PV array connected in series then connected into single inverter in **figure b**, and a multistring PV is when multiple PV string are connected to a single DC bus then connected to a DC/AC inverter.

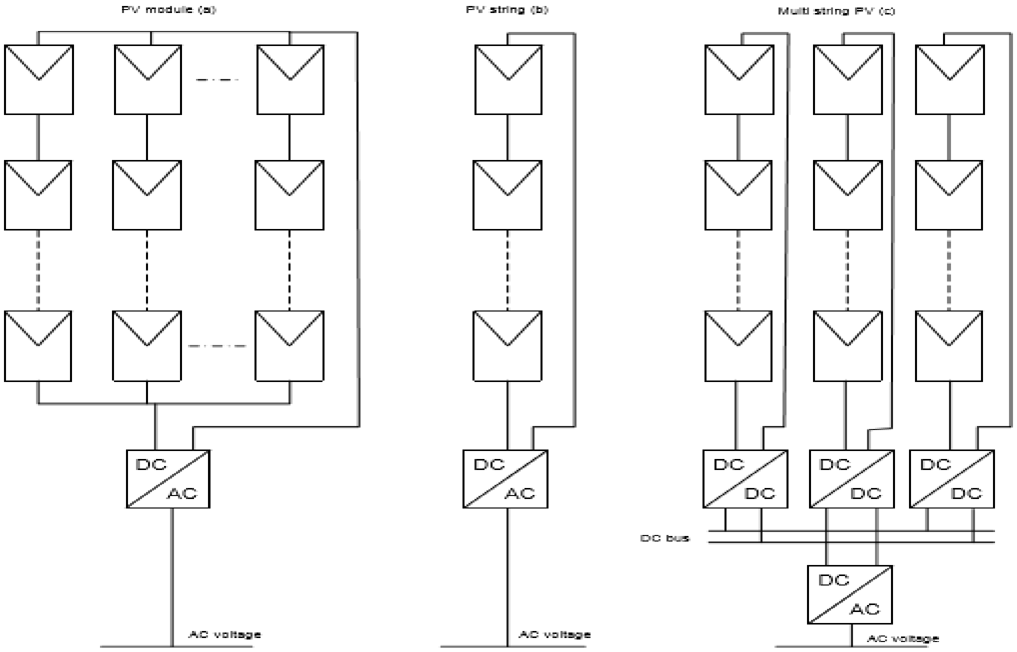


Figure 3.13 Topology of PV module, PV string and multi string PV

3.4.2 Central inverters or single stage photovoltaic system

Central inverter topology can be called also single stage photovoltaic. In this topology, the photovoltaic system includes a series-parallel connection arrangement, which is connected to a single inverter DC/AC for the transferal of the higher amount of power possible to the grid or the load. Single stage photovoltaic is shown in figure 3.14 It has one inverter DC/AC that must handle the MPPT, control the current on the grid along with the amplification of the voltage, which makes the single stage more complex to control. Using conventional H-bridge inverter followed by step up transformer or using a PV array with sufficiently large PV voltage. Thus, the boost converter is no longer necessary. However, the extra transformer adds up to the cost and the size of the PV system. In addition, the large PV array has the disadvantage of reduced safety and increased probability of leakage current through the parasitic capacitance between the panel and the system ground. In single stage PV system, the dc/ac inverter must ensure all the functions: MPPT, boosting and inversion as shown in figure 3.15. The central inverter topology is cheap, robust and highly efficient. The major disadvantage is the low power factor 0.6 and 0.7. The actual PWM full bridge inverter, switched at great frequencies improves the efficiency of the system.

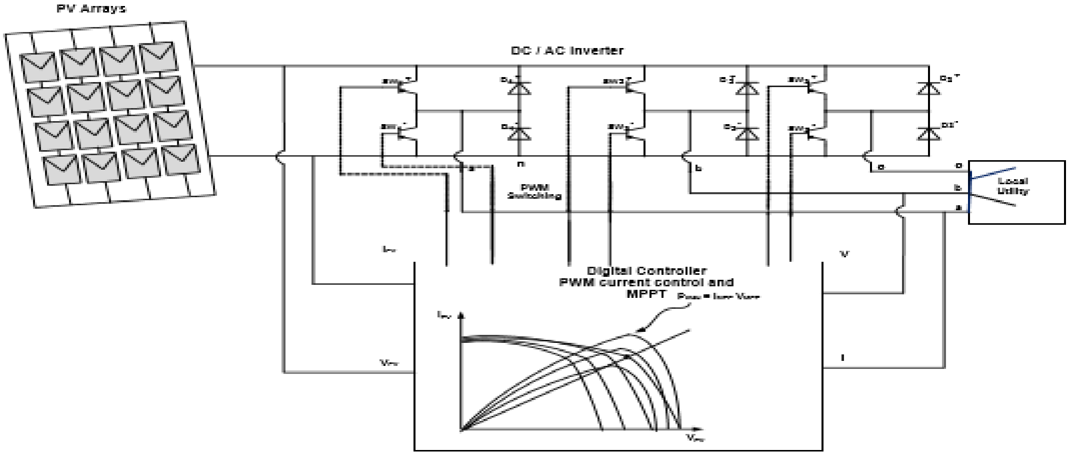


Figure 3.14: Circuit diagram of DC/AC grid-connected PV system

3.4.3 String inverter or two stages photovoltaic system

The photovoltaic modules in the given topology are linked in a structure whereby they end up forming a string; the voltage from the PV array ranges between 150-450 V. The DC/DC converter realizes the MPPT along with the amplification of the voltage. The DC/AC inverter controls the grid current with a pulse width modulation (PWM) control scheme. The initial stage is utilized as a means to boost the voltage for the PV array and track MPP of solar power; subsequent to this, the second phase coverts the dc power into ac power. The two stages have the following drawbacks of lower effectiveness, higher count for parts, lower level of reliability, bigger size and higher cost. This topology is mostly used due to its simplicity. The two-stage PV system is shown in figure

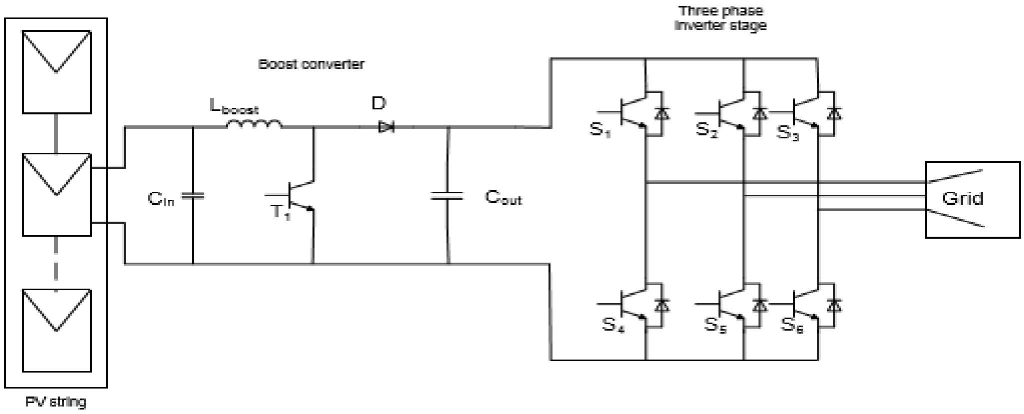


Figure 3.15: Two stage PV system with boost converter and three-phase inverter

3.4.4 Multi string inverter

In this topology, "multiple PV module or string is connected to a dedicated dc-dc converter that is connected to a common dc-ac inverter. Each PV string has its own boost converter and MPPT. Each PV operates at MPP. Figure 3.16 represents the multi string inverter and can be noted that each dc-dc converters typically link with each other by means of DC bus via an inverter. The advantage with multistring inverter is its ability to add an extra PV module to the bus if more power is needed in the future. In case of failure of one PV string, the PV system still able to operate with the remaining PV.

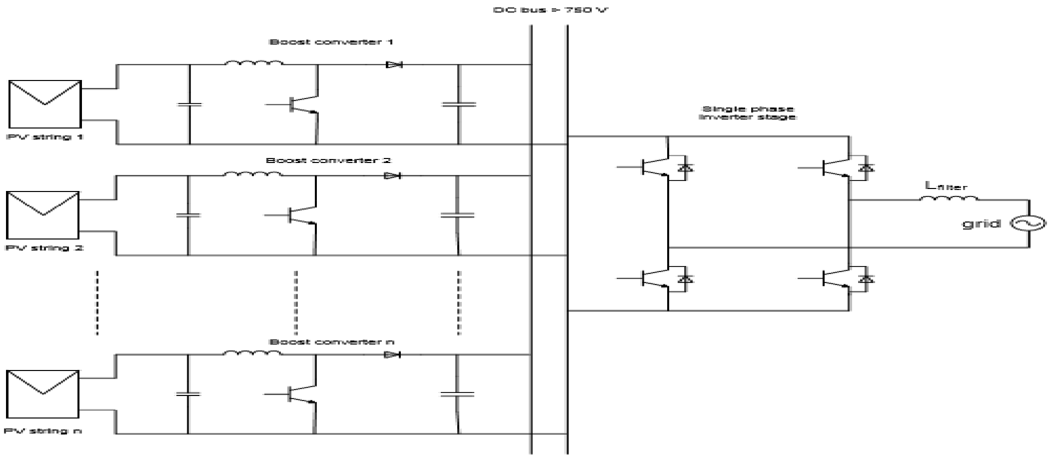


Figure 3.16: Multistring PV system

3.4.5 SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

The DC-AC inverters usually operate on Pulse Width Modulation (PWM) technique. The PWM is a very useful technique in which width of the gate pulses are controlled by various mechanisms.PWM inverter is used to keep the output voltage of the inverter at the rated voltage irrespective of the output load. The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and strong control scheme. Depending on the switching performance and good characteristic features, Sinusoidal Pulse Width Modulation (SPWM) will be used and the modulating signal as illustrated in Fig 3.17. the advantages of using SPWM include low power consumption, high energy efficient up to 90%, high power handling capability, no temperature variation-and aging caused drifting or degradation in linearity and SPWM is easy to implement and control. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. Figure 3.17 shows the waveform of the sine triangle and the voltage reference comparison.

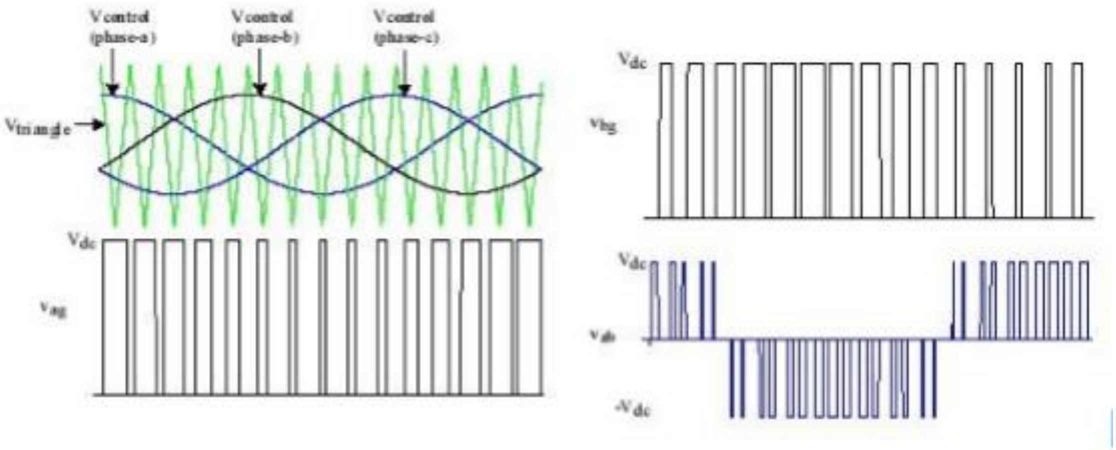


Figure 3.17: Sine triangle, voltage reference and phase voltage

In sine triangle PWM, the amplitude modulation ratio (or index) ma is defined by

$$m_a = \frac{peak\ amplitude\ of\ V_{tria}}{amplitude\ of\ V_{ref}}$$

where

V_{tria}: the peak amplitude of the triangular carrier

V_{ref} :peak amplitude of the sinusoidal reference signal

The frequency of the triangular waveform f_{pwm} is the frequency of the inverter.

The frequency of the reference is the fundamental output frequency. For a grid connected PV, it is the frequency of the grid 60 Hz. The ratio of those two frequencies gives the frequency modulation index

$$m_f = \frac{PWM\ frequency\ f_{pwm}}{fundamental\ frequency\ f_1}$$

3.5 Specifications and standards for grid connected PV systems

The grid-connected standards covered the topics about voltage, DC current injection, flicker, frequency, harmonics current, maximum current, total harmonics distortion (THD) and power factor.

3.5.1 Islanding:

A condition in which the photovoltaic system and its load remain energized while disconnected from the grid.

3.5.2 Distributed resource islanding:

An islanding condition is when the photovoltaic sources of energy supply the loads not from the utility system.

3.5.3 Non-islanding inverter:

An inverter ceases to energize the utility line

3.5.4 Grounding

NEC 690 standard requires the system and interface equipment should be grounded and monitored. It gives more safety and protection in case of ground faults inside the PV system.

3.5.5 Voltage disturbances

The utility company set the voltage of grid network. The PV system cannot control the voltage of the grid so the output voltage of the PV has to be within the operating range defined by the standards. The inverters should detect abnormal voltages and prevent islanding of the system. The PV systems remain connected to the grid and should reconnect when the voltage was restored. The voltage operating range is detailed in IEEE standard 929.

3.5.6 DC component injection

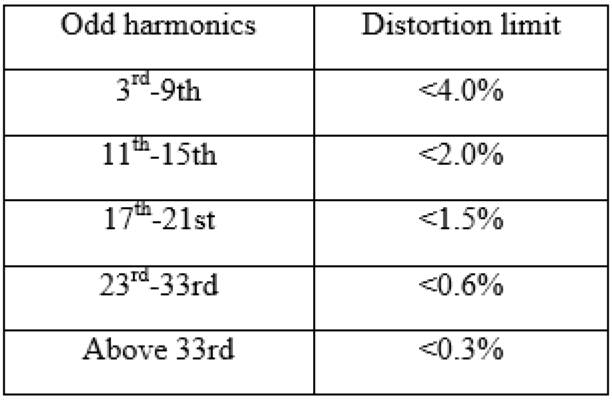
According to IEC 61727, the DC current injected should be less than “0.5% of rated inverter output current into the utility AC interface.” The DC current could produce inundation of the delivery converters within the grid.

3.5.7 Total Harmonic Distortion

The topology has to be chosen along with the modulation scheme of the inverters should give an AC current with low level of harmonic distortion. High current harmonics can cause adverse effects on the diverse equipment connected to the grid. Table gives the maximum limit of acceptable distortion current. The table shows the output harmonics current for six pulse inverters. “Total harmonic current distortion shall be less than 5% of the fundamental

frequency current at rated inverter output.

- Even harmonics shall be < 25 % of the odd harmonics limits



Odd harmonics	Distortion limit
3rd-9th	<4.0%
11th-15th	<2.0%
17th-21st	<1.5%
23rd-33rd	<0.6%
Above 33rd	<0.3%

Table 3.1: Harmonics current limits for six-pulse converters

3.5.8 Voltage flicker

The voltage flicker should not exceed the maximum limits in IEC 61727.

3.5.9 Islanding protection

The inverters must have a feature that can identify a situation of islanding and respond accordingly to safeguard the people and equipment involved. For instance, the standard stated that the inverter should disconnect from the utility line when there is disturbance from the system. In islanding, the inverters continue to supply local loads even in the case that the grid is no longer connected to the inverter. Inverters that are tied to the grid overlook the utility line and can turn themselves off with great speed if required (in 2 seconds or less) in the event that abnormalities occur on the utility system The principal concern is that a utility line worker could be exposed to a line that is unexpectedly energized

3.5.9.1 Power factor

The IEEE standard929 specifies that the power factor of the PV system should be > 0.85 (lagging or leading) when output is >10%. The grid connected PV inverter is designed to have a control current with a power factor unity. Sometimes the inverter is used for reactive power compensation; therefore, the inverter should be capable to control the output power factor.

3.5.9.2 Reconnect after disturbance

The PV system should not be reconnected until continuous normal voltage and frequency are maintained by the utility for a minimum of five minutes, at which time the inverter can automatically reconnect.

3.5.9.3 Frequency

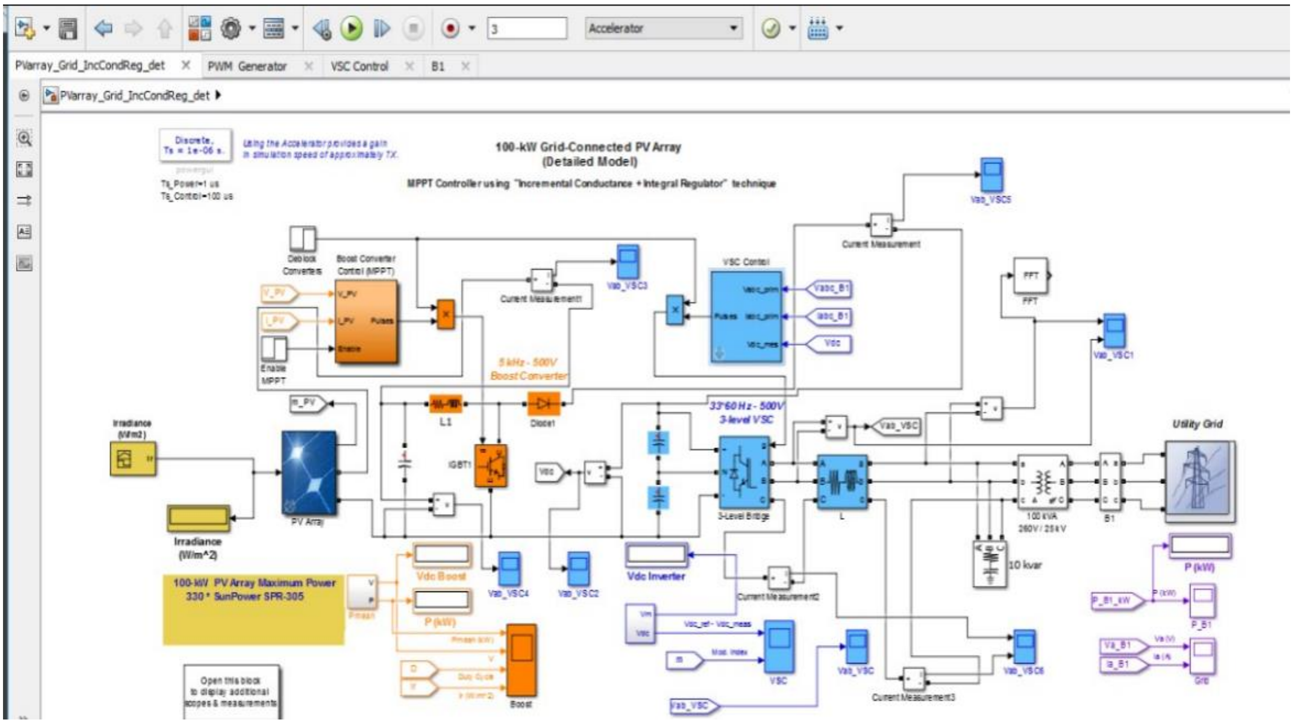
The PV systems should have a fixed frequency between 59.3 – 60 Hz. The PV systems should stay synchronized with the grid. For small PV systems, the frequency trip should be 59.2 Hz and 60.6 Hz. When there is variation of frequency outside the range specified above, the inverter has to stop energizing the line of utility within a span of over six cycles. The time delay is set to avoid the PV to trip for short time disturbance

3.6 CONCLUSION

In this chapter, the maximum power point tracking problem is discussed, and the boost type of DC-DC converters, which is the main tool used for obtaining the maximum power point are mentioned. The operation of the boost converter is also discussed. Further on, different famous MPPT algorithms are mentioned and their advantages and disadvantages are also highlighted, and then the three main algorithms used in this thesis (P&O and ICT) are discussed in more details along with the control scheme of the DC-AC inverter. The system topology of the grid connected inverter and a mathematical model of a photovoltaic cell has been developed. In conclusion the grid requirements for photovoltaic technology have been explained from the recommendations of international standardisation

CHAPTER 04:

Simulation of the grid connected Photovoltaic System Using Matlab / Simulink



4.1 Introduction

This chapter describes the Grid connected solar photovoltaic system using DC-DC boost converter and the DC/AC inverter (VSC) to supply electric power to the utility grid. The model contains a representation of the main components of the system that are: a solar array of 100 kW, boost converter and the grid side inverter. The maximum power point algorithm incorporated in a DC/DC converter is used to track the maximum power of PV cell and the Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the "Incremental Conductance + Integral Regulator" technique. Finally, the DC/AC inverter (VSC) of three- levels and a current control unit provide an AC voltage that meets the grid requirements for connection and synchronization. Simulation results show how a solar radiation's change can affect the power output of any PV system, also they show the control performance and dynamic behaviour of the grid connected photovoltaic system.

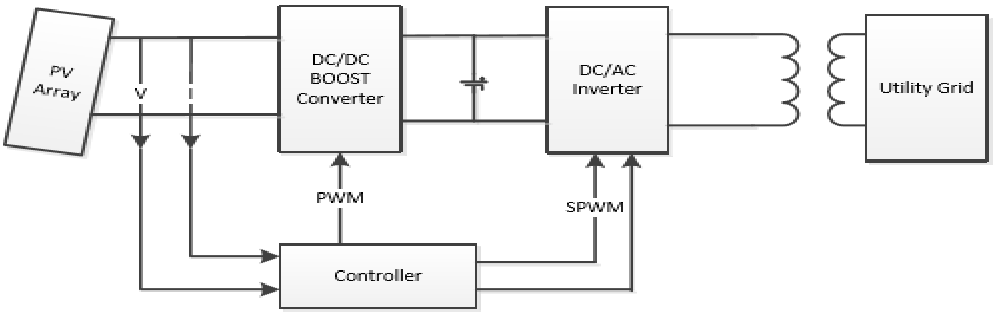


Figure 4.1 Grid connected photovoltaic system

4.2 Simulation of the photovoltaic array

Simple PV cell (ECEN2060)

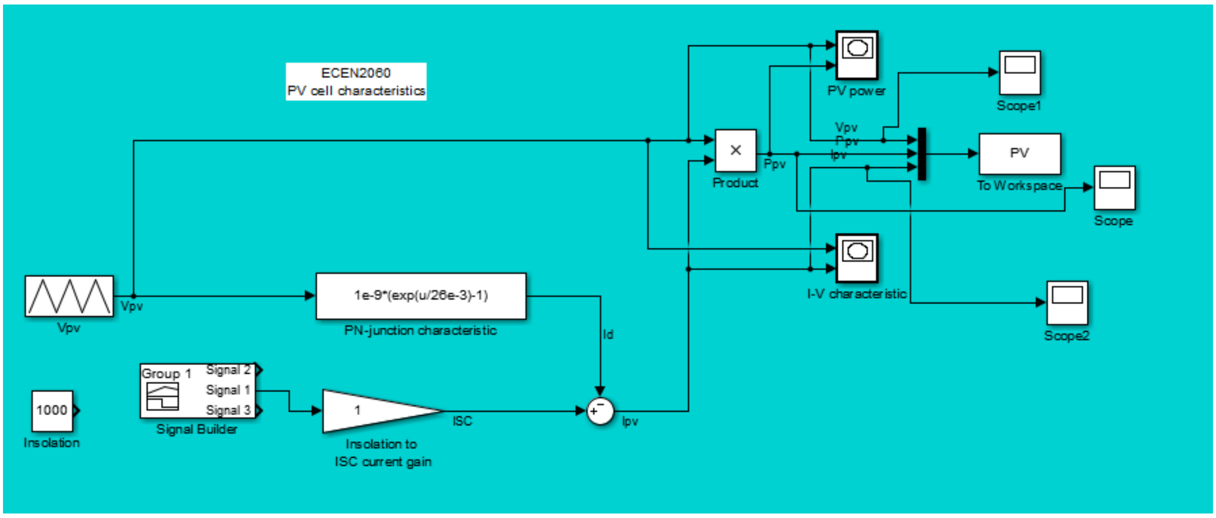


Figure 4.2: Simple PV cell Simulink model (Simulation stop time: t =1)

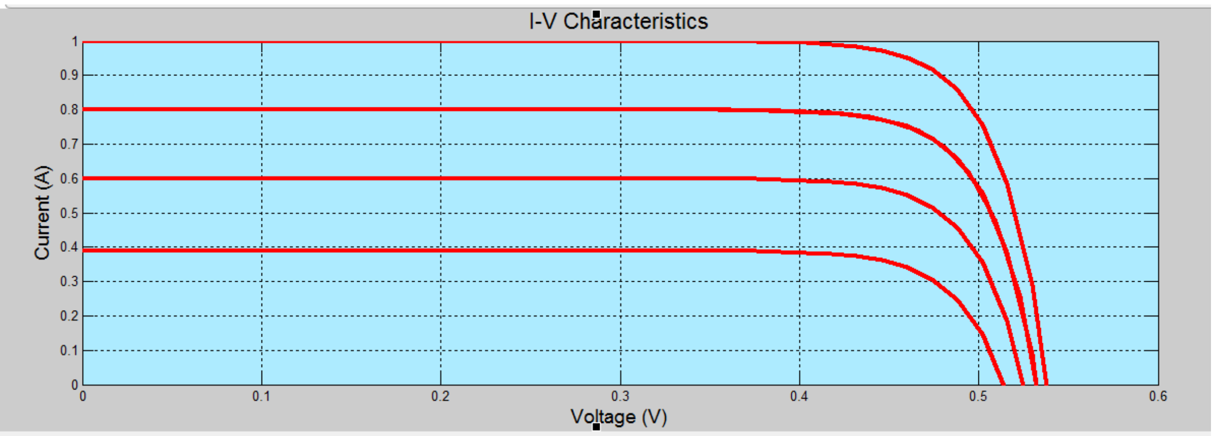


Figure 4.3: I-V Characteristics (Result of fig 4.2)

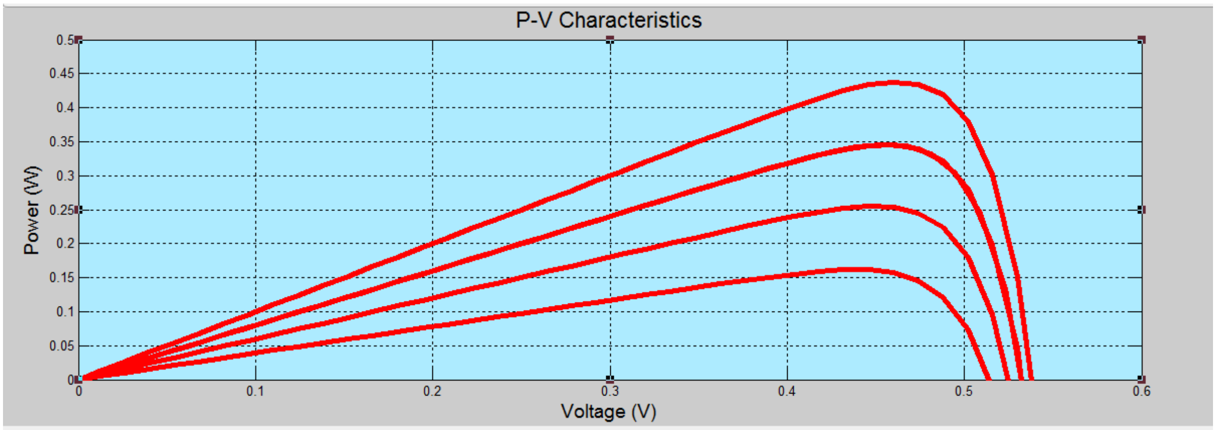


Figure 4.4: P-V Characteristics (Result of fig 4.2)

4.3 Full System description of the simulation a grid connected 100 KW PV Array.

Figure 2 shows a PV array of 100kW connected to a 25kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the Incremental Conductance + Integral Regulator technic. The proposed model contains the following components:

a. PV arrays delivering a maximum of 100 kW at 1000 W/m² sun irradiance.

b. DC-DC boost converter that is used to increase the voltage output of PV to 500 V DC.

c. Three-level three-phase VSC inverter that is used to convert the DC voltage delivered by the array of (500 V) to an AC voltage of 260 V and also to keep a unity power factor.

d. Capacitor Banks of 10 kVar used to filter the harmonics produced by the VSC.

e. A three-phase coupling transformer of 100 kVA. And 260/25kV.

f. Utility grid.

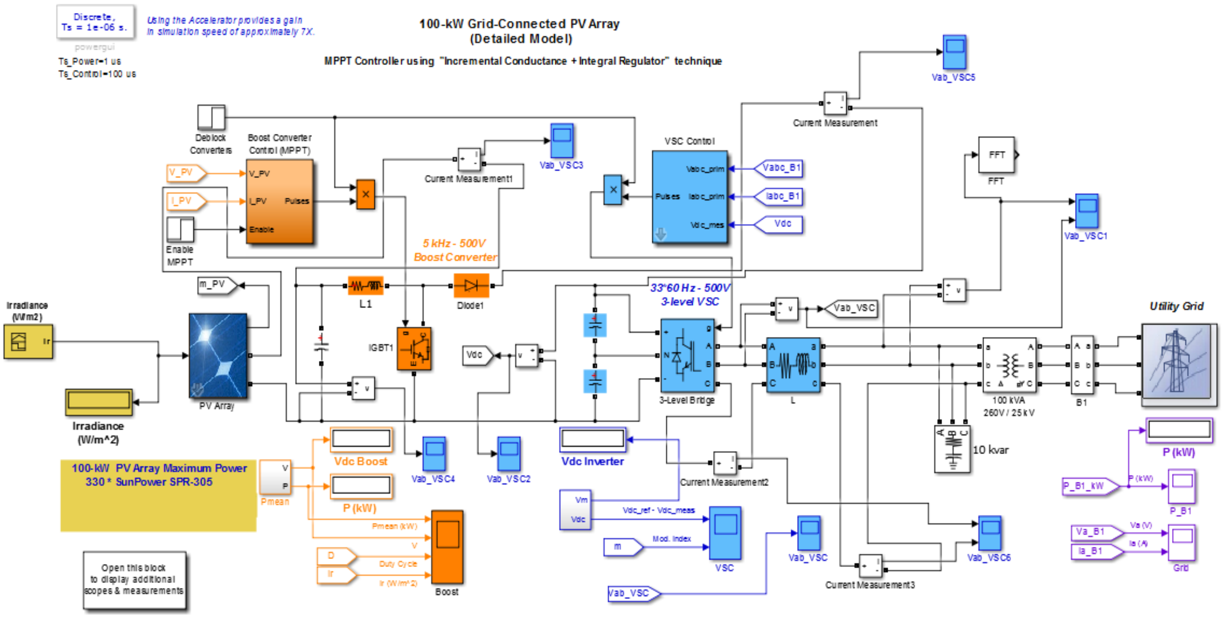


Figure 4.5: Whole PV grid-connected system

4.3.1 The photovoltaic generator

The 100-kW PV array « Sun Power (SPR-305) », consists of 66 strings of 5 series-connected 305.2W modules connected in parallel (66*5*305.2 W= 100.7 kW). Manufacturer specifications for the module « SPR-305 » are listed in Table 1. The PV array block has one input that allows varying sun irradiance (input 1 in W/m²). The irradiance profile is defined by a Signal Builder block which is connected to the PV array inputs. The characteristics I-V and P-V of one module SunPowerSPR-305-WHT type are represented below.

Model name	SunPower SPR-305-WHT
No. of cells	96 in series
Open circuit voltage (Voc)	64.2 V
Short circuit current (Isc)	5.96 A
Maximum Power Voltage(Vmp)	54.7 V
Maximum Power Current (Imp)	5.58 A

Table 4.1: Specifications of « Sun Power (SPR-305) » PV-array

The PV array block menu allows you to plot the I-V and P-V characteristics for one module and for the whole array. The characteristics of the SunPower-SPR305 array are reproduced below.

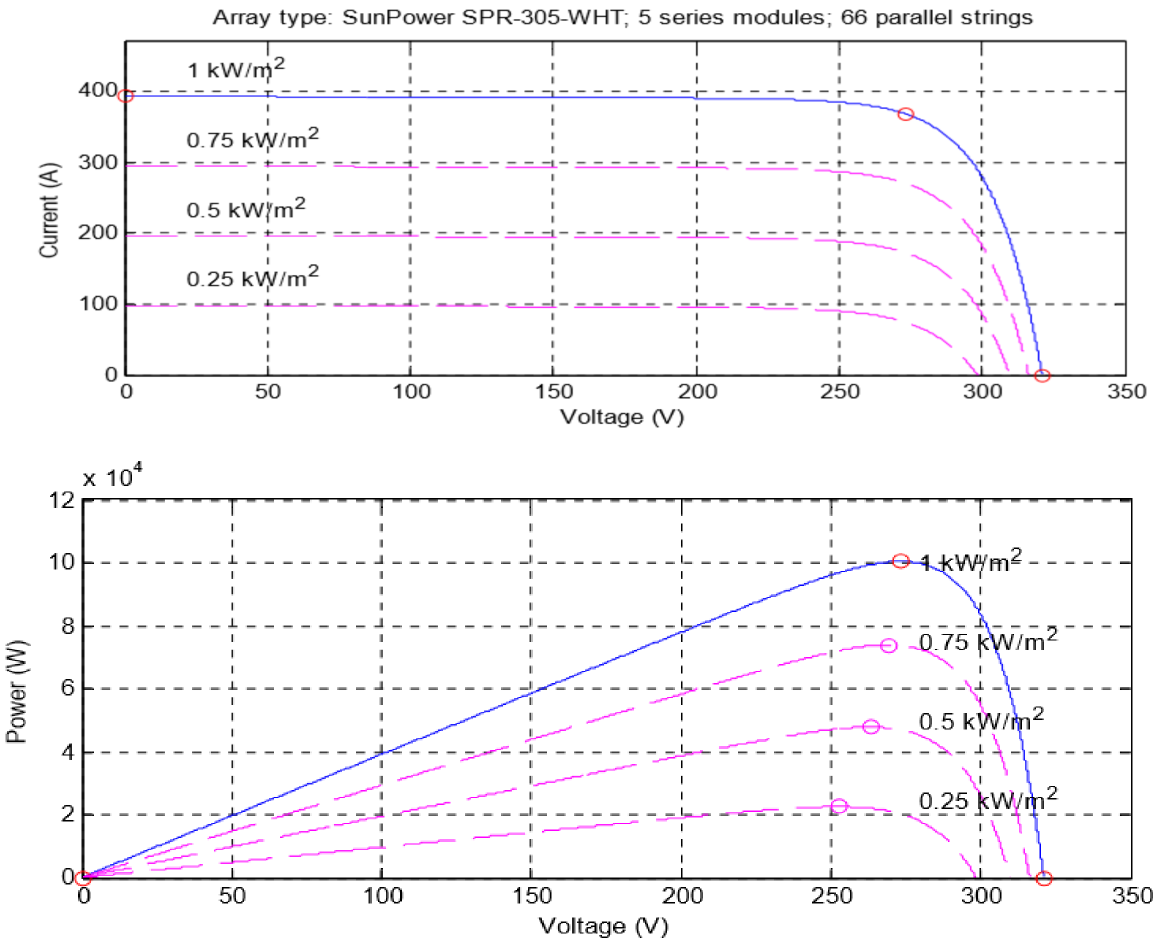


Figure 4.6 I-V and P-V characteristics of PV array

Red dots on blue curves indicate module manufacturer specifications (Voc, Isc, Vmp, Imp) under standard test conditions (25 degrees Celsius, 1000 W/m2).

4.3.2 Boost converter

In the detailed model, the boost converter (orange blocks) boosts DC voltage from 273.5 V to 500V. This converter uses a MPPT system which automatically varies the duty cycle in order to generate the required voltage to extract maximum power. To connect solar system to the utility grid we have to increase the magnitude of the output voltage. Which can be done with the use of a DC-DC converter, here we use Boost converter to increase the level of source voltage to higher levels. Fig 4.7 shoes the Simulink model of boost converter. Converter consists of an input dc voltage source, controlled switch (IGBT), diode, inductor coil, filter capacitor C1 and C2. When the switch is ON, the current in the inductor increases linearly and the diode is in OFF state. When the switch is OFF the energy stored in the inductor will be released through diode to the RC circuit. The output voltage is directly proportional to the duty ratio of the converter.

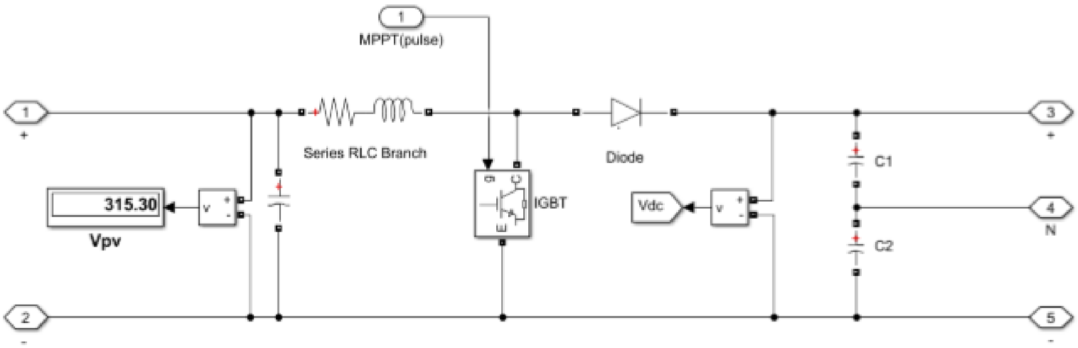


Figure 4.7. Boost converter subsystem

4.3.3 INCREMENTAL CONDUCTANCE CONTROLLER

The incremental conductance algorithm discussed in chapter 3 is constructed using MATLAB/ SIMULINK TOOLBOX, and its output is connected to the boost converter to achieve the maximum power point tracking. Fig 4.8 shows the SIMULINK model of the MPPT using ICT method.

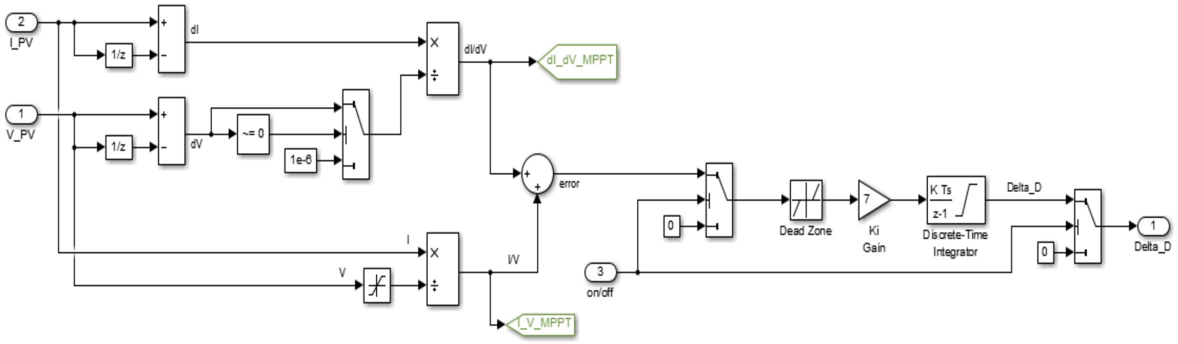


Figure 4.8: Maximum Power Point Controller Using ICT

4.3.4 Modelling of Inverter with current control unit

A significant part of a grid connected PV system is the inverter and its control unit for grid synchronization. The control unit includes a Phase Locked Loop (PLL) controller, which is used for the synchronization of the PV system with the grid. Fig 4.9 shows the Simulink subsystem of inverter with current control loop for grid synchronization. It consists of a three-level power inverter that consists of three arms of power switching devices. Each arm consists of four switching devices along with their antiparallel diodes and two neutral clamping diodes. The current controller of the inverter consists of PLL, Vdc regulator, current regulator, reference generator and Pulse Width Modulation (PWM) generator. Vdc regulator measures DC voltage and compare it to the reference voltage. PLL control unit convert grid voltage and current from abc to dq reference frame by using Park's transformation. The grid voltage is uncontrollable, the most effective way of controlling the operation of the system is by controlling direct current (Id) and quadrature current (Iq) that are flowing to the grid. As active power is dependent on the current Id, so to inject real power to the grid, Id must be set to zero. Current controller consists of integral controller used to set Id = 0, thus reactive power injection to the grid set to zero. The output of current controller is fed into the switching pulses through PWM generator to generate the gate pulses of inverter.

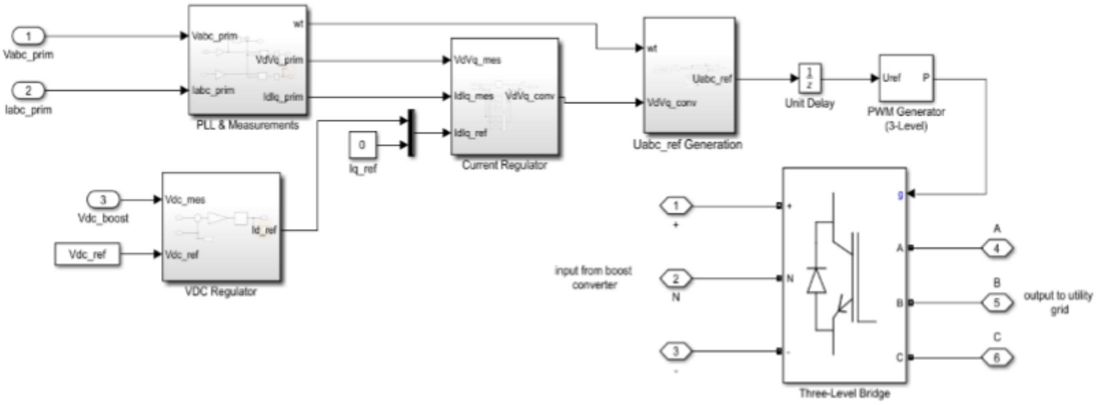


Figure 4.9: Inverter with current control subsystem

4.3.5 MATLAB/SIMULINK MODEL OF GRID CONNECTED SYSTEM

Fig 4.10 shows the simulation model of two-stage, grid connected PV system. Here the PV array delivers output power as per the standard test conditions with module temperature of 298 K (25 °C) and irradiance of 1000 W/m2. The boost converter is used to step-up the PV voltage from 273.5V to 500V. The duty cycle of the boost converter is controlled by MPPT controller. Inverter converts 500V DC into AC voltage. To compensate the harmonics produced by inverter, 10kvar capacitor bank is used. A 100kVA three phase transformer is used to connect the solar system to 25kV utility grid.

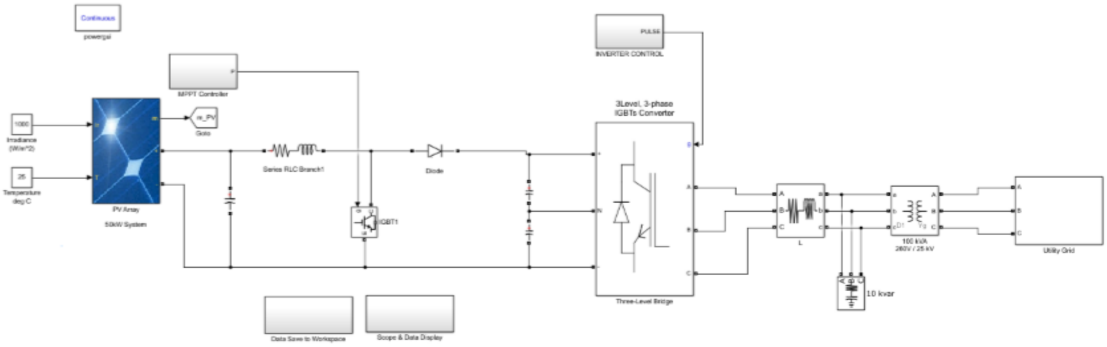


Figure 4.10: Simulink model of two-stage three phase grid connected 100kW PV array

4.4 SIMULATION RESULTS AND DISCUSSION

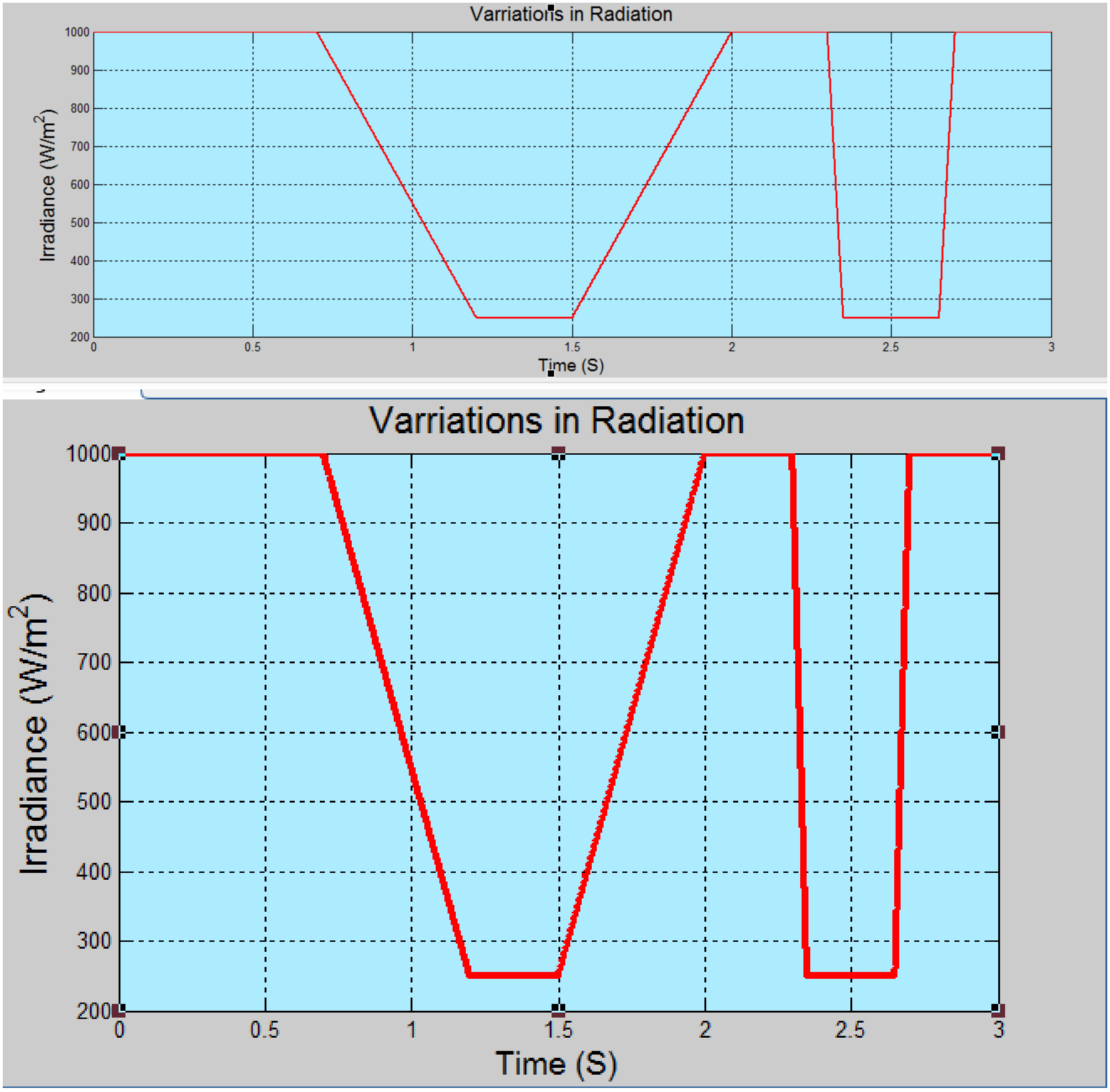
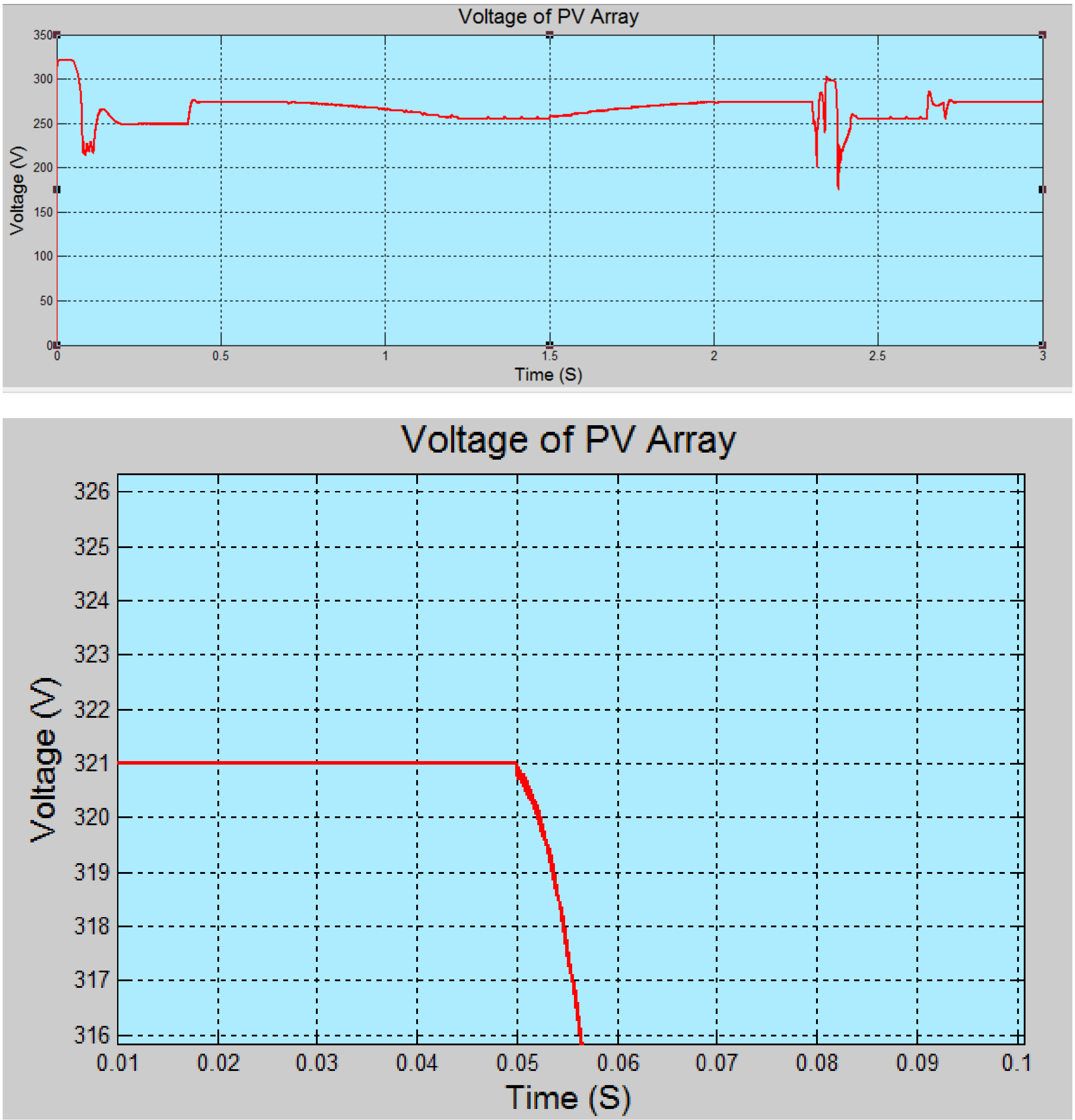


Figure 4.11: Irradiance of the PV array and zoom



<u>Fig 4.12: Waveform of output voltage of PV array and zoom</u>

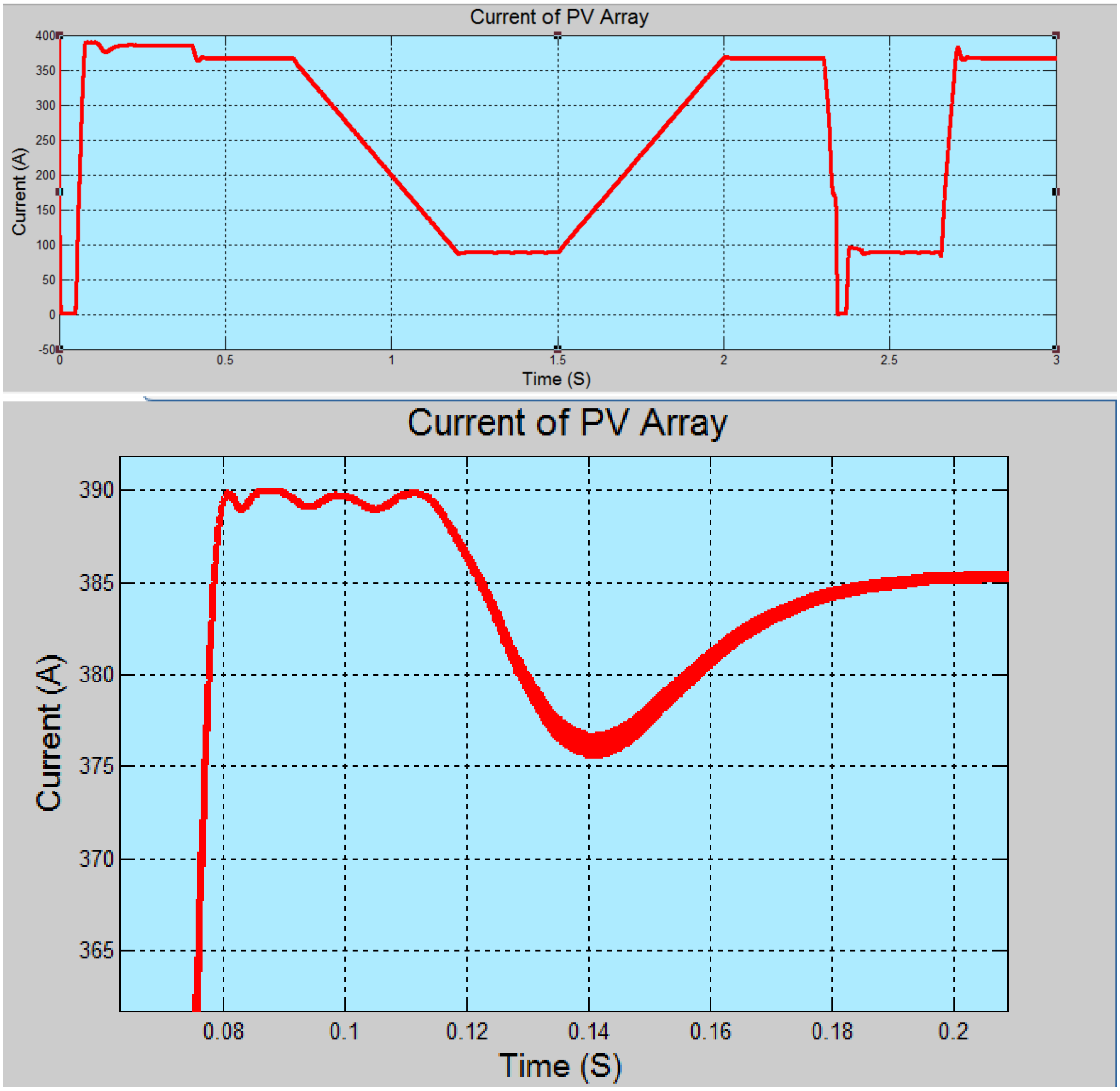


Fig 4.13: Waveform of output current of PV array and zoom

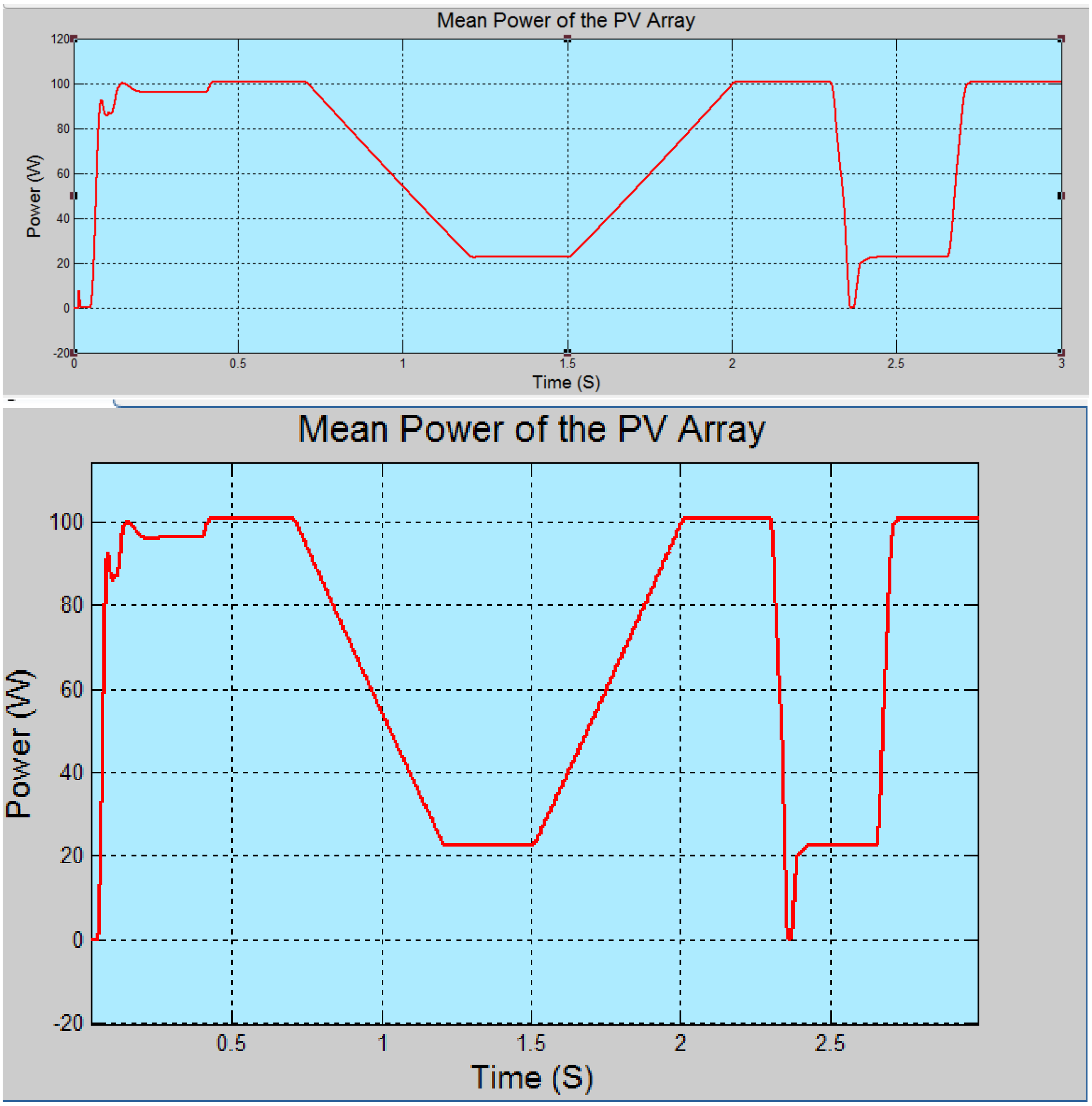


Figure 4.14: Waveform of output power of PV array and zoom

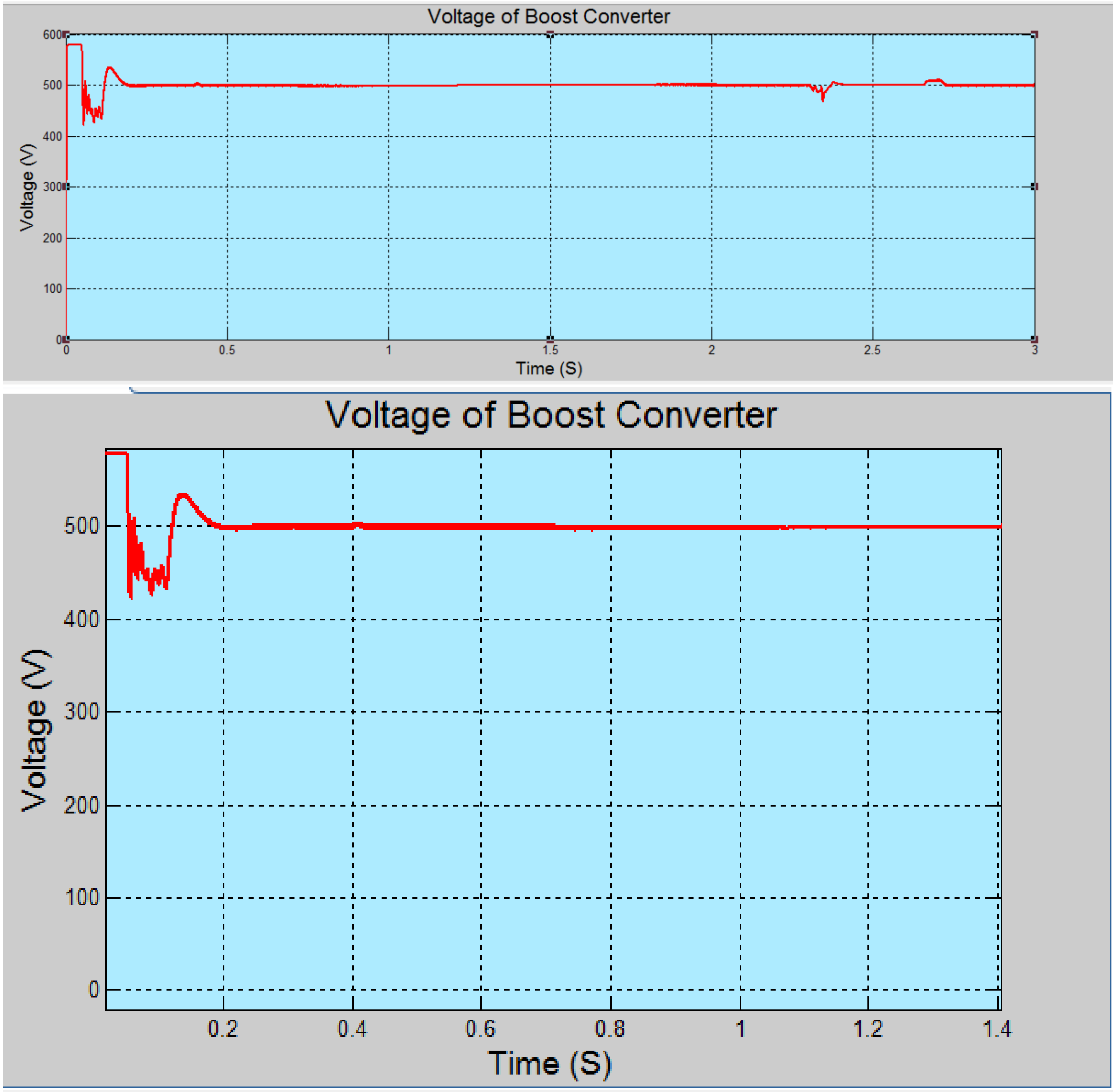


Figure 4.15: Waveform of output voltage of Boost converter and zoom

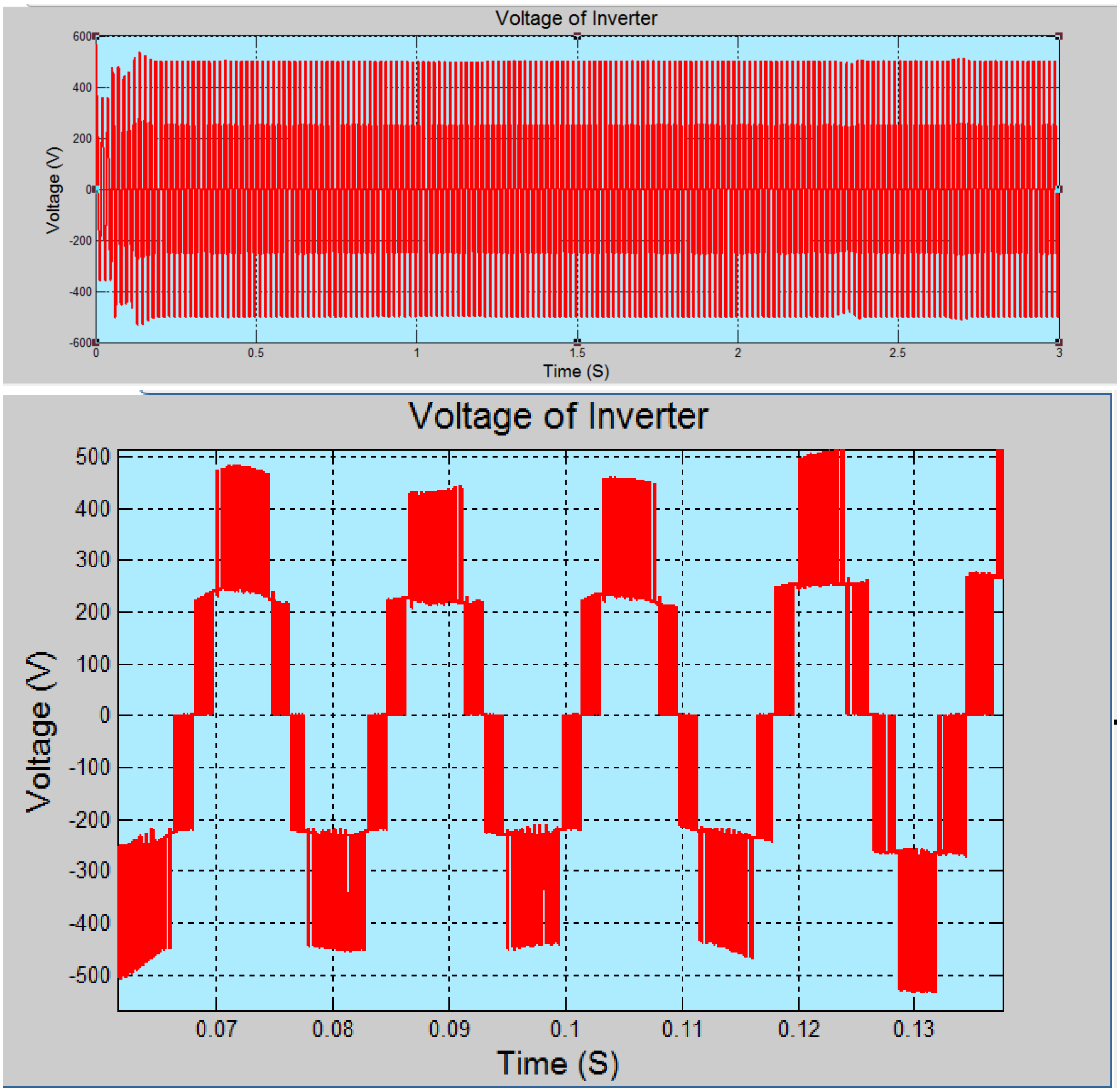


Figure 4.16: Waveform of output voltage of inverter before AC link

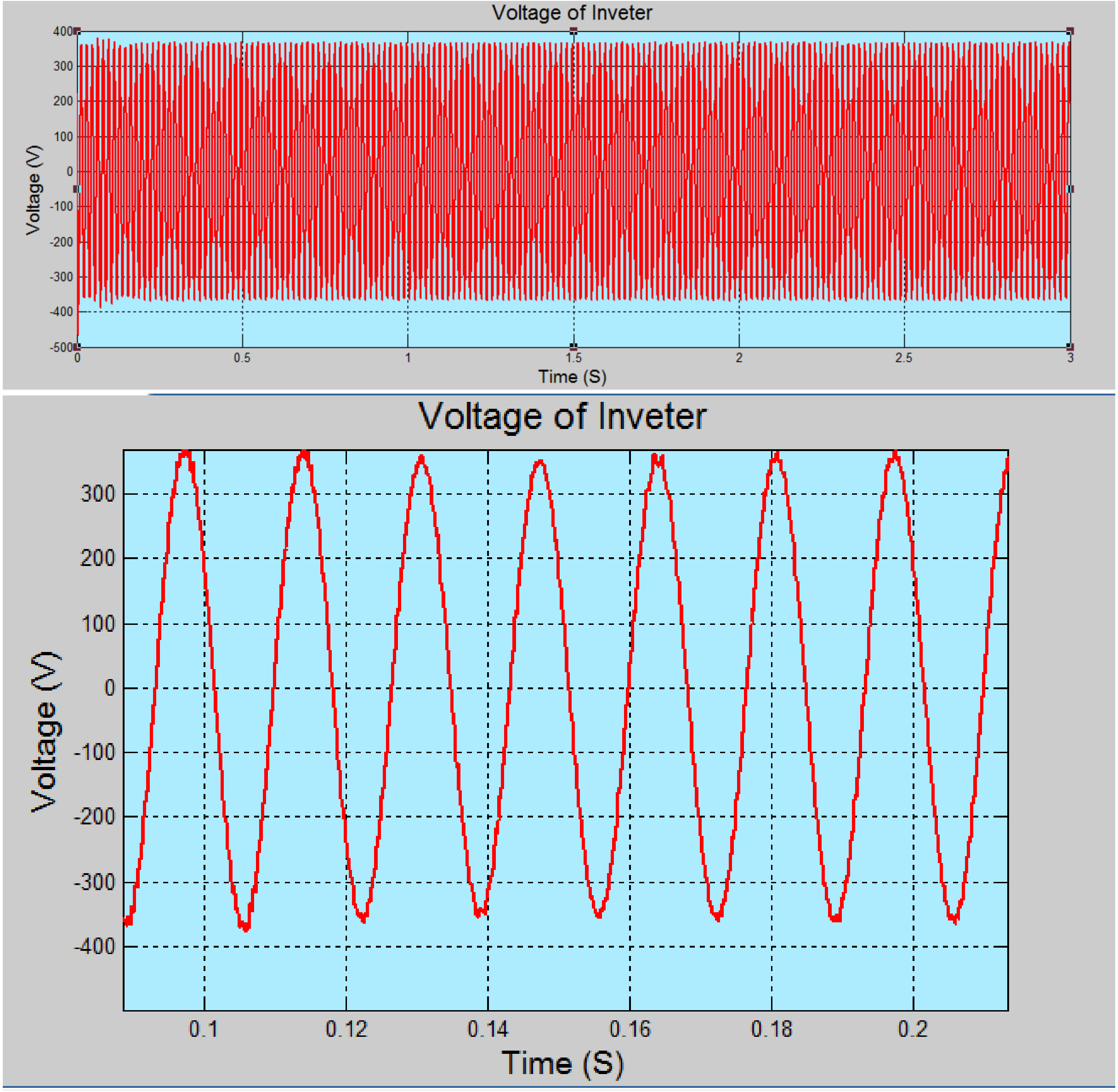


Figure 4.17 Waveform of output voltage of inverter after the AC link

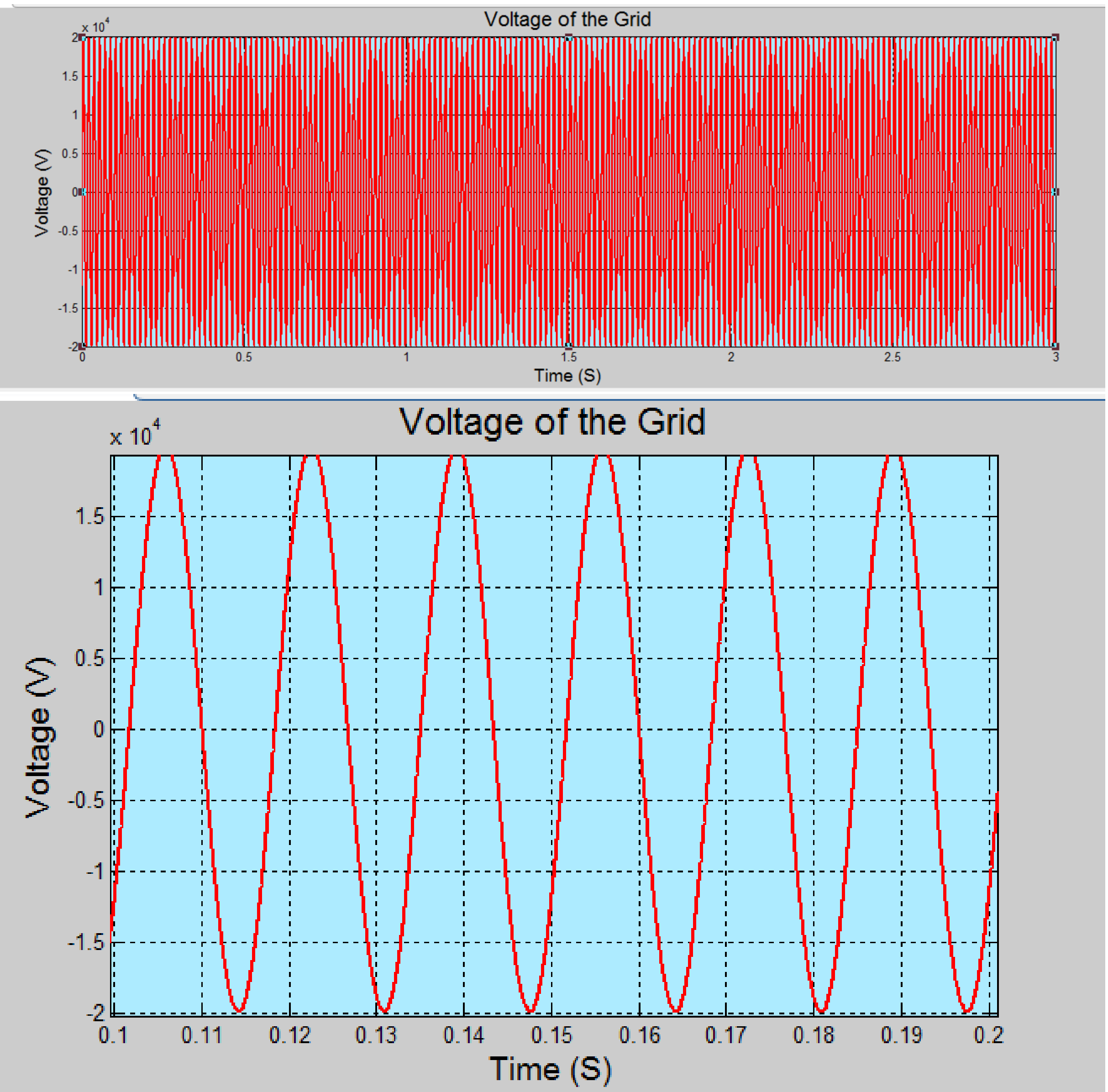


Figure 4.18: Waveform of the grid voltage

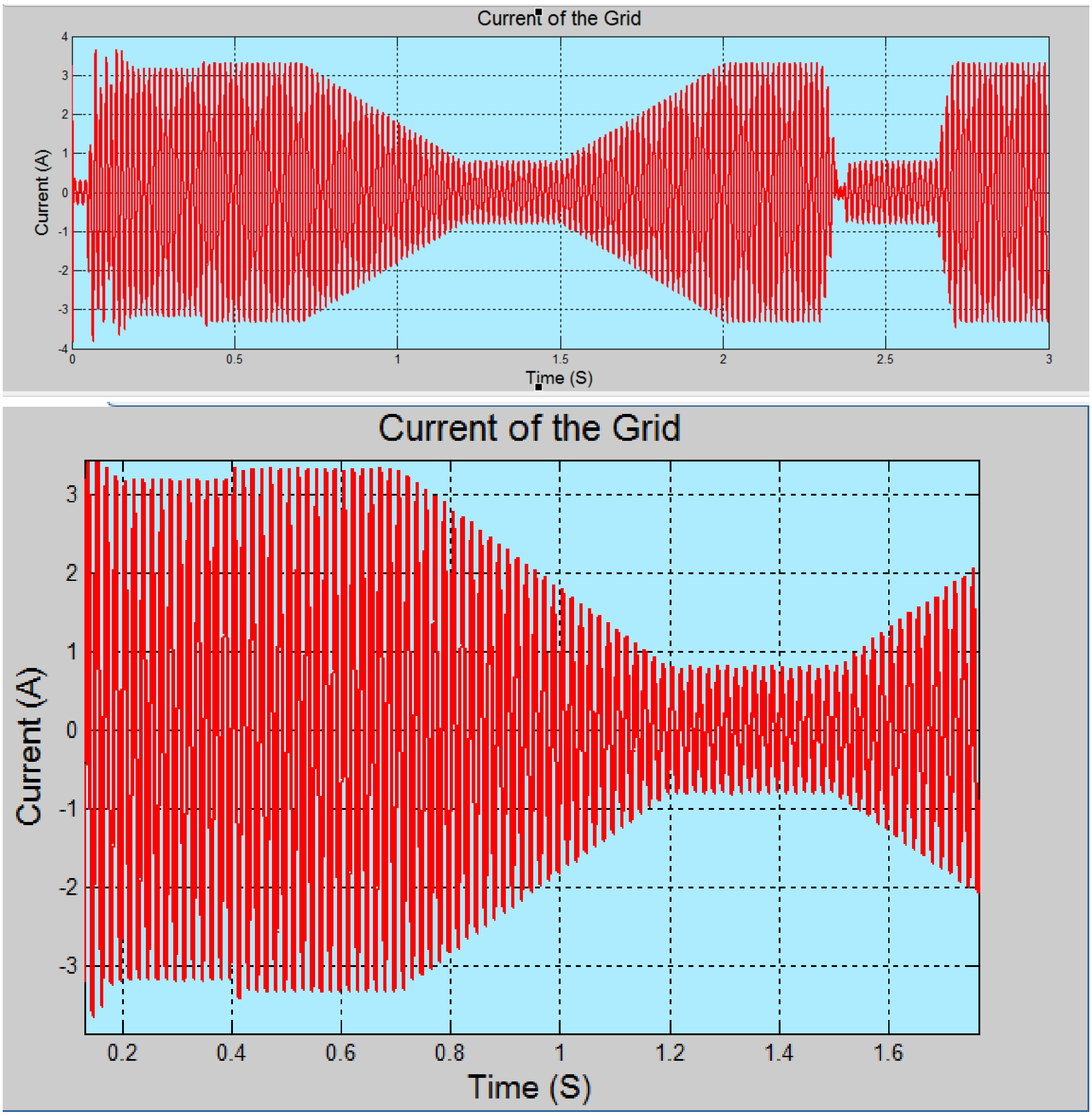


Figure 4.19: Waveform of Current injected into the grid

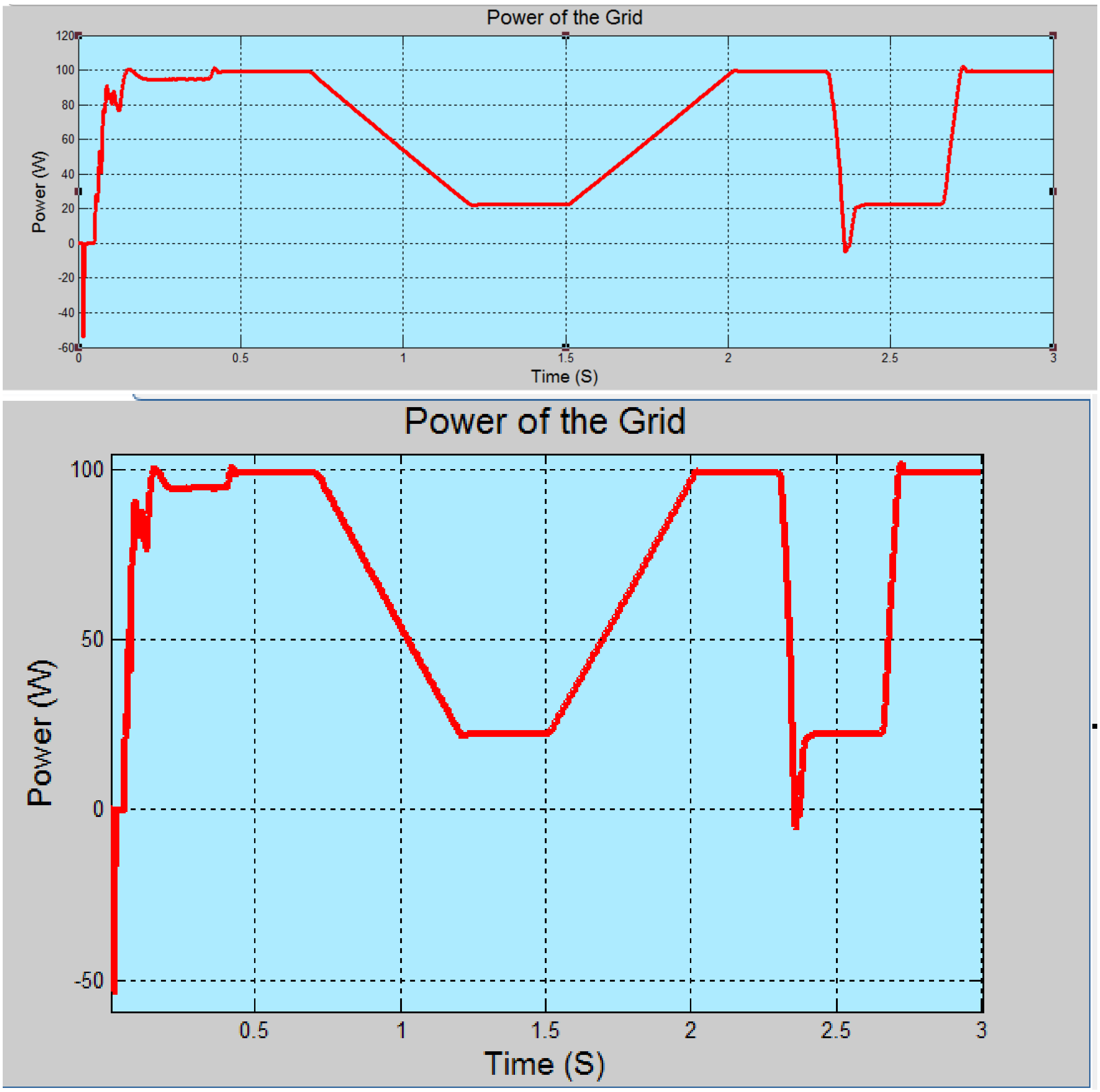


Figure 4.20: Waveform of power injected into the grid

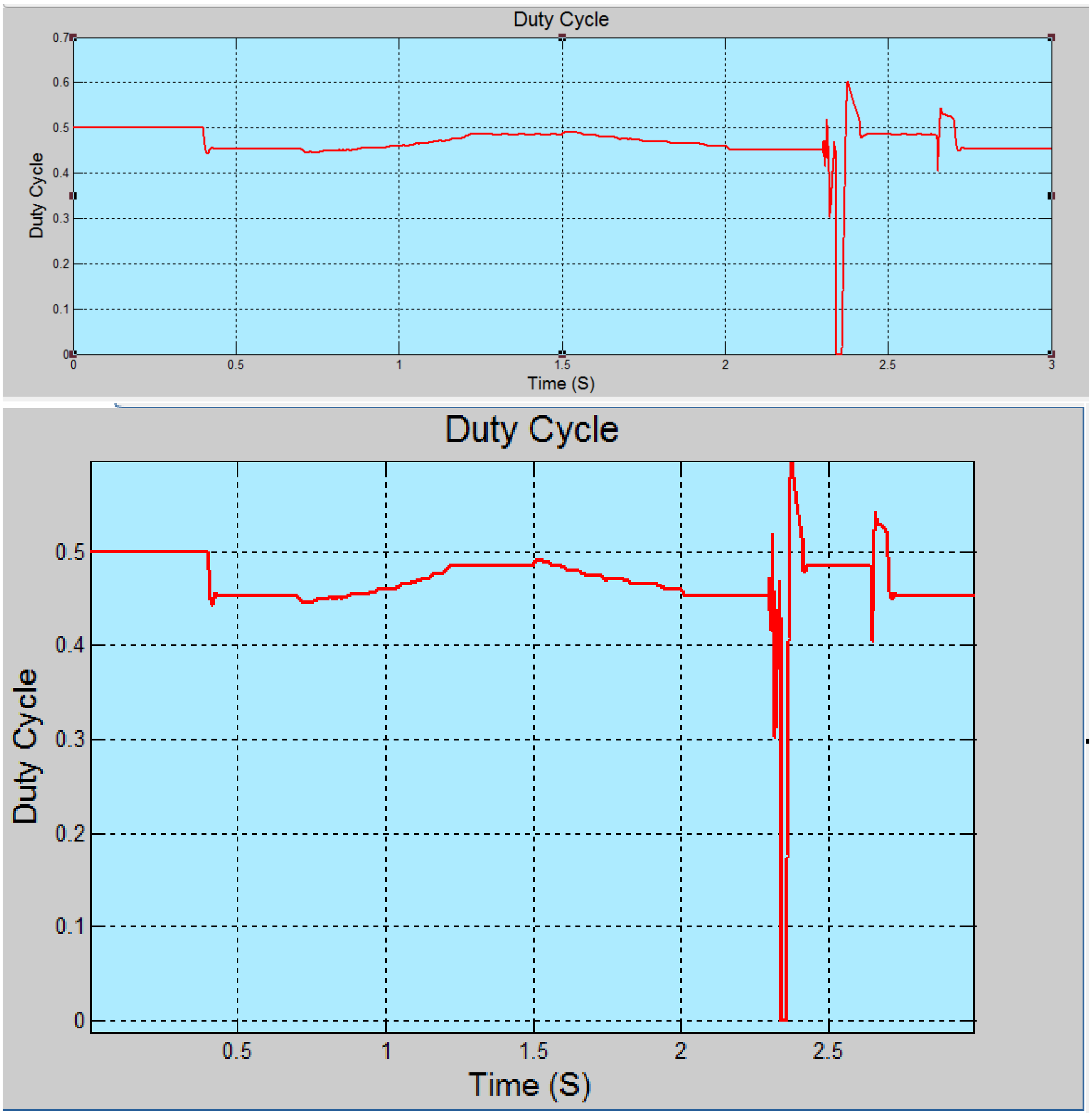


Figure 4.21: Duty cycle of the PV array

4.5 DISCUSSION

- From t=0 sec to t= 0.05 sec, pulses to Boost and VSC converters are blocked. PV voltage corresponds to open-circuit voltage (**Nser*Voc=5*64.2=321 V**, see V trace on Scope Boost). The three-level bridge operates as a diode rectifier and DC link capacitors are charged above 500 V (see Vdc_meas trace on Scope VSC).
- At t=0.05 sec, Boost and VSC converters are de-blocked. DC link voltage is regulated at Vdc=500V. Duty cycle of boost converter is fixed (D= 0.5 as shown on Scope Boost) and sun irradiance is set to 1000 W/m2. Steady state is reached at t=0.25 sec. Resulting PV voltage is therefore **V_PV = (1-D)*Vdc= (1-0.5)*500=250 V** (see V trace on Scope Boost). The PV array output power is 96 kW (see Pmean trace on Scope Boost) whereas maximum power with a 1000 W/m2 irradiance is 100.7 kW. Observe on Scope Grid that phase A voltage and current at 25 kV bus are in phase (unity power factor).
- At t=0.4 sec MPPT is enabled. The MPPT regulator starts regulating PV voltage by varying duty cycle in order to extract maximum power. Maximum power (100.7 kW) is obtained when duty cycle is D=0.453. At t=0.6 sec, PV mean voltage =274 V as expected from PV module specifications **(Nser*Vmp=5*54.7= 273.5 V)**.
- From t=0.7 sec to t=1.2 sec, sun irradiance is ramped down from 1000 W/m2 to 250 W/m2. MPPT continues tracking maximum power. At t=1.2 sec when irradiance has decreased to 250 W/m2, duty cycle is D=0.485. Corresponding PV voltage and power are Vmean= 255 V and Pmean=22.6 kW. Note that the MMPT continues tracking maximum power during this fast irradiance change.
- From t=1.5 sec to 3 sec various irradiance changes are applied in order to illustrate the good performance of the MPPT controller.
- Figure 19 shows the power injected into the grid. From t = 0 s to t = 0.05 s the power injected into the grid is growing because the pulses of boost converter and VSC inverter are blocked. At t = 0.05s the pulses are enabled, the power injected into the grid is 96 kW. From t = 0.2 s to t = 0.75 s the irradiance is 1000W / m², while the injected power reaches its maximum value. From t = 0.75 s to t = 2.75 s several variations in the irradiance lead to change the power injected into the grid to stabilize at 2.75 s and takes the value of 100 kilowatts.

4.6 CONCLUSION

This Chapter presents the modelling and simulation of grid connected PV system with "Incremental Conductance + Integral Regulator" technique, MPPT Algorithm to inject the power extracted from a photovoltaic array and obtain unitary power factor in varying weather conditions. According to the results obtained from the simulation, we can say that it is essential to operate the system at the MPP (Maximum Power Point) of a PV array, in other words we should always extract the maximum power from the PV module by modulating the duty cycle of the boost converter in order to enhance the power injected into the grid, otherwise the PV array is not fully exploited which consequently is reflected by a higher losses in the energy transferred from the PV array to the utility grid. Also the Pulse width modulation (PWM) technique has been developed beside inverters. So that we can obtain a sinusoidal waveform at the output of the inverter and the total harmonic distortion (THD) of the output voltage can be reduced. The results confirm the adequate performance of whole designed control.

4.7 Final conclusion

In this thesis, the study of a grid-connected photovoltaic system with maximum power point controller has been developed. From the theory of the photovoltaic, a mathematic model of the PV has been presented. Then, the photovoltaic system with DC-DC boost converter, maximum power point controller with an inverter connected to the grid have been designed. Finally, the system has been simulated with Simulink MATLAB. First, the simulations of the PV panels showed that the simulated models were accurate to determine the characteristics of voltage and current because the current-voltage characteristics are the same as the characteristics given from the data sheet. In addition, when the irradiance or temperature varies, the PV models output voltage current changes too. Then, the simulation showed that “Incremental Conductance + Integral Regulator” algorithm can track the maximum power point of the PV, it always runs at maximum power no matter what the operation condition is. The results showed that the algorithm delivered an efficiency close to 100% in steady state. The simulations of the PV with maximum power point, boost converter and the grid were performed by varying the irradiance and the temperature. Finally, the PV performance and the maximum power point were analysed, and the three phase full bridge DC-AC inverter was simulated while connected to the grid. The results showed that the DC voltage generated by the PV array could produce an AC current sinusoidal at the output of the inverter which has almost the same output waveform of that of the grid. The amplitude of the current depends on the PV power.

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