IMPROVEMENT OF VOLTAGE PROFILE

IN

HYBRID RENEWABLE ENERGY SYSTEM

DISSERTATION II

Submitted in partial fulfillment of the

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PHAGWARA (DISTT. KAPURTHALA), PUNJAB

(School of Electronics & Electrical Engineering)

Lovely Professional University

Punjab

(APRIL 2017)

CERTIFICATE

This is to certify that the Thesis titled **"IMPROVEMENT OF VOLTAGE PROFILE IN HYBRID RENEWABLE ENERGY SYSTEM"** that is being submitted by **"SHASHANK SHUKLA"** is in partial fulfillment of the requirements for the award of MASTER OF TECHNOLOGY DEGREE, is a record of bonafide work done under my /our guidance. The contents of this Thesis, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma and the same is certified.

Mrs. Navita

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Lovely Professional University

Objective of the Thesis is satisfactory / unsatisfactory

ExaminerI **Examiner II**

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my mentor **“Mrs. Navita”** Assistant Professor for her guidance, encouragement, and support throughout the course of this work. It was an invaluable learning experience for me to be one of her students. From her, I have gained not only extensive knowledge but also a sincere research attitude. I express my gratitude to Head of the Department, of Electrical Engineering for her invaluable suggestions and constant encouragement all through the research work. My thanks are extended to my friends in “Power Electronics & Power System” who built an academic and friendly research environment that made my study at Lovely Professional University, Phagwara most memorable and fruitful.

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CERTIFICATE

This is to certify that the declaration statement made by this student is correct to the best of my knowledge and belief. He is doing Dissertation-II work under my guidance and supervision. The present work is the result of their original investigation, effort, and study. No part of the work has ever been submitted for any other degree at any University. The Dissertation-II work is fit for the submission and partial fulfillment of the conditions for the award of M.Tech degree in Electrical Engineering from School of Electronics and Electrical Engineering, Lovely Professional University, Phagwara.

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CANDIDATE'S DECLARATION

I Shashank Shukla, student of M.Tech (Electrical Engineering) from School of Electronics and Electrical Engineering, Lovely Professional University, Punjab, hereby declare that all the information furnished in this dissertation report is based on my own work carried out under the supervision of Mrs. Navita, Assistant Professor, School of Electronics and Electrical Engineering. The matter presented in this dissertation has not been submitted to Lovely Professional University or to any other university or institute for the award of any degree.

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ABSTRACT

Renewable energy sources have become a popular alternative electrical energy source where power generation in conventional ways is not practical. Wind and solar are by far the fastest growing renewable energy resources due to their free availability and environmental benefits. In the last few years the photovoltaic and wind power generation have been increased significantly. In this study, a hybrid energy system which combines both solar panel and wind turbine generator have been proposed as an alternative for conventional source of electrical energy like thermal and hydro power generation. The common disadvantage of both wind and solar power plants are as these generate unreliable power.

In order to overcome this problem, this dissertation proposes MPPT technique (IC) and new topology of MLI which reduces more THD content from output waveform than conventional one. These proposed methods are used in both photovoltaic and wind power generation. Simulation of PV plant is done by the use of MATLAB 2016a. Boost converter is used to boost up the output voltage of PV array and the controlling of switch of boost converter is done by the use of MPPT technique (IC). The THD content present in the voltage and current at the AC side of inverter is reduced using five level inverter. Enhancement of power quality is the main aim of this dissertation work.

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ABBRIVATION

AC	Alternating Current
CMLI	Cascade multi-level inverter
CDMs	Clean department mechanisms
CSP	Concentrating solar power
CIS	Copper indium diselenide
CdTe	Cadmium telluride cells
DCMLI	Diode clamped multi-level inverter
DC	Direct Current
DG	Distributed generator
FCMLI	Flying capacitor multi-level inverter
FACTS	Flexible ac transmission system
HAWT	Horizontal Axis Wind Turbine
IGBT	Insulated-Gate Bipolar Transistor
IC	Incremental conductance
MATLAB	Matrix Laboratory
MI	Modulation index
MPM	Multi pules width modulation
MLI	Multi-level inverter
MPPT	Maximum power point tracking
MPP	Maximum power point
MV	Medium voltage
PIV	Peak inverse voltage

PCS	Power conditioning system
PV	Photo voltaic
P&O	Perturb and observe
PLC	Programmable logic controller
PMSG	Permanent magnet synchronous generator
SCR	Silicon controlled rectifier
SPV	Solar photo voltaic
SDCS	Separate DC source
SPWM	Sinusoidal pulse width modulation
SVPWM	State vector pulse width modulation
SHESW	Selective harmonics elimination stepped waveform
THD	Total harmonic distortion
TSR	Tip Speed Ratio
UPS	Uninterrupted power supply
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion System
WT	Wind turbine

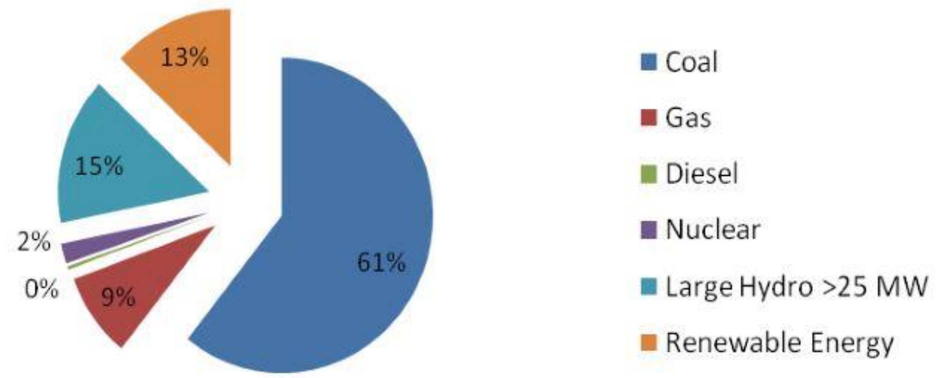
CHAPTER- 1

INTRODUCTION

1.1 Background

Renewable energy is energy generated from natural resources- such as sunlight, wind, rain, tides and geothermal heat; which are renewable (naturally replenished). Renewable energy technologies range from solar power, wind power, hydroelectricity/micro hydro, biomass and biofuels for transportation.

Alternative energy is a term used for an energy source that is an alternative to using fossil fuels. Generally, it indicates energies that are non-traditional and have low environmental impact. The term alternative is used to contrast with fossil fuels according to some sources. By most definitions, alternative energy doesn't harm the environment, a distinction which separates it from the renewable energy which may or may not has significant environmental impact.



Coal	Gas	Diesel	Nuclear	Hydro	Renewable
173	24.5	1	5.78	42.6	37.4

Figure 1.1: Renewable energy shared in India 2016.

1.2 The need for renewable energy

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike dwindling conventional fossil fuels. The global energy crunch has provided a renewed impetus to the growth and development of Clean and Renewable Energy sources. Clean Development Mechanisms (CDMs) are being adopted by organizations all across the globe. Apart from the rapidly decreasing reserves of fossil fuels in the world, another major factor working against fossil fuels is the pollution associated with their combustion. Contrastingly, renewable energy sources are known to be much cleaner and produce energy without the harmful effects of pollution, unlike their conventional counterparts.

1.3 Different sources of renewable energy

1.3.1 Wind power

Wind energy is another viable option. The Wind Turbine Generator is designed for optimal operation at a wind speed of 10-14 m/s. The Turbine Generator starts at a cut-in speed of 3-3.5 m/sand generate power at speeds 4.5 m/s and above. In India, the best wind speed is available during monsoon from May to September and low wind speed during November to March. The annual national average wind speed considered is 5-6 m/s.

Figure 1.2: Diagram of wind energy system.

Wherever average wind speed of 4.5 m/s. and above is available it is also an attractive option to supplement the energy supply. Wind turbines can be used to harness the energy available in airflows. Current day turbines range from around 600 kW to 5 MW of rated power. Since the power output is a function of the cube of the wind speed, it increases rapidly with an increase in available wind velocity. Recent advancements have led to aerofoil wind turbines, which are more efficient due to a better aerodynamic structure.

1.3.2 Solar power

In India, the annual global solar radiation is about 5 KWh/ sq. m per day with about 2300-3200 sunshine hours per year. Solar radiations represent the earth's most abundant energy source. The perennial source of solar energy provides unlimited supply, has no negative impact on the environment.

Figure 1.3: Diagram of solar energy system.

The solar photovoltaic (PV) modules convert solar radiation from the sun into electrical energy in the form of direct current (DC). Converting solar energy into electricity is the answer to the mounting power problems in the rural areas. Its suitability for decentralized applications and its environment-friendly nature make it an attractive option to supplement the energy supply from other sources. 1 KW of SPV generates 3.5-4.5 units (KWhr) per day. If we could install Solar Photovoltaic

Cells much of the rural exchange power needs could be met, adequately cutting down harmful greenhouse gasses. PV generation efficiency and power quality are the fundamental issues. PV power sources are usually integrated with control algorithms that have the task of ensuring maximum power point (MPP) operation. [24] Many algorithms have been developed for tracking the maximum power point of a solar array. Most commonly used are the perturb-and-observe (P&O) algorithm and the incremental conductance algorithm. The tapping of solar energy owes its origins to the British astronomer John Herschel who famously used a solar thermal collector box to cook food during an expedition to Africa. Solar energy can be utilized in two major ways. Firstly, the captured heat can be used as solar thermal energy, with applications in space heating. Another alternative is the conversion of incident solar radiation to electrical energy, which is the most usable form of energy. This can be achieved with the help of solar photovoltaic cells or with concentrating solar power plants.

1.3.3 Small hydropower

Hydropower installations up to 10MW are considered as small hydropower and counted as renewable energy sources. These involve converting the potential energy of water stored in dams into usable electrical energy through the use of water turbines. Run-of-the-river hydroelectricity aims to utilize the kinetic energy of water without the need of building reservoirs or dams.

1.3.4 Biomass

Plants capture the energy of the sun through the process of photosynthesis. On combustion, these plants release the trapped energy. This way, biomass works as a natural battery to store the sun’s energy and yield it on the requirement.

1.3.5 Geothermal

Geothermal energy is the thermal energy which is generated and stored within the layers of the Earth. The gradient thus developed gives rise to a continuous conduction of heat from the core to the surface of the earth. This gradient can be utilized to heat water to produce superheated steam and use it to run steam turbines to generate electricity. The main disadvantage of geothermal energy is that it is usually limited to regions near tectonic plate boundaries, though recent advancements have led to the propagation of this technology.

1.4 Solar-wind hybrid energy system

Hybrid Wind-Solar System for the rural exchanges can make an ideal alternative in areas where wind velocity of 5-6 m/s is available. Solar-wind power generations are clear and non-polluting. Also, they complement each other. During the period of bright sunlight, the solar energy is utilized for charging the batteries, creating enough energy reserve to be drawn during night, while the wind turbine produces most of the energy during monsoon when solar power generation is minimum. Thus the hybrid combination uses the best of both means and can provide quality, stable power supply for sustainable development in rural areas. [18]

Figure 1.4: Photovoltaic-wind hybrid energy system.

1.4.1 Why a hybrid system?

Over the present years, hybrid technology has developed and upgraded its role in renewable energy sources while the benefits it produces for autonomous power production are unchallenged. Nowadays many houses in rural and urban areas use hybrid systems. Many isolated islands try to adopt this kind of technology because of the benefits which can be received in comparison with a single renewable system.

More specifically for a wind/solar hybrid system, the assessment is focused on the wind and solar potential of the region. Therefore it can be operated during the day using the energy from the sun and after the sun has set it can utilize the potential wind energy to continue its function. For this reason, wind and solar systems work well together in a hybrid system and they provide a more consistent year-round output than either wind-only or PV-only system. Finally, it is economically sound and advantageous to use non-finite resources, i.e. solar and the wind (hybrid). The investment financially and environmentally in modern technologies will win through the generations to come in the fight for energy efficiency and effectiveness.

1.5 Objectives

The main objective of this dissertation work is to implement a power system that is a hybrid combination of both Photovoltaic and wind farms, which are given below;

- To study and model PV cell, PV panels and PV array.
- To study the characteristic curves of PV and wind farm and effect of variation of environmental conditions like temperature, irradiation and wind speed as well.
- To track the maximum power point of operation of PV panel irrespective of the changes in the environmental conditions.
- To study and simulate the wind power system and track its maximum power point.
- Implement hybrid system.
- In future intelligent devices like microprocessors, PLC (programmable logic controller) may be added to the system to keep the operating point (maximum power point) for maximum efficiency. If the hybrid system can control by using the same controlling method it will provide better performance and cost will be less.

CHAPTER- 2

LITERATURE REVIEW

Ajami, et.al; [2016]: proposed a six switch converter which is basically based on the PMSG having MPPT capability. It works as a rectifier to incorporate two variables wind turbine which is relied upon PMSG (permanent magnet synchronous generator). Maximum power point tracking (MPPT) is used in order to achieve higher efficiency. In low power applications, this approach is efficient in terms of cost. Also, this proposed technique enhances its reliability, reduces its weight and also its size. MATLAB /SIMULINK are used for its performance and results. [1]

Nguyen et.al; [2015]: In this study, Analysis of sensorless MPPT algorithm has been proposed.This strategy comprises of wind turbine, doubly fed induction generator and photovoltaic system .this strategy is then compared with the separate system with MPPT system. [2]

M. F. Elmorshedy et.al; [2015]: This paper present controlling procedure for an off grid WECS using a permanent magnet synchronous generator (PMSG). In this initially, DC link voltage is controlled by the duty cycle. Therefore, to convert the voltage of the DC link to the amplitude and to the required frequency of the charging voltage, a sinusoidal pulse-width modulation (SPWM) for controlling the inverter. The presented control strategy aims to regulate the load voltage in terms of magnitude and frequency in different operating conditions, including wind speed. Wind generation system under consideration he uses PMSG with a wind turbine, AC-DC, DC-DC and DC-AC converter. The control strategy is presented based in part on control of the duty cycle, Converter to convert the input variable to DC voltage, because to different operating conditions, at a suitable constant DC voltage. Therefore, a modulated sinusoidal pulse width (SPWM) UPS is used to adjust the amplitude and frequency by controlling the modulation index. A sample simulation results are obtained and analyzed here. [3]

Ritesh Dash et.al;-[2015]: The maximum efficiency of the PV system is just about 25-30. The hybrid system generally consists of either a DC bus or an AC bus. Different types of energy sources are connected to the DC and AC bus through proper conversion system and hence maintain the integrity. [4]

P. Loganthurai et.al; [2014]: The optimal sizing for wind solar-battery hybrid power system according to the system working in grid-connected and stand-alone modes is carried out in the system.. [5]

Anila Prabha et.al; [2014]: In this paper, the buck-boost converter used in WECS and a sinusoidal pulse width modulation and SVPWM are modeled and compared with a WECS with Z-source inverter. How much energy a wind turbine can produce will depend on wind resource at the site, the size of wind turbine, rotor swept the area, nominal power and how efficient turbine can convert the kinetic energy of wind. [6]

Chih-Chiang Hua et.al; [2013]: The proposed system consists of a wind generator, a boost converter, and a full-bridge inverter. In this system, a digital signal processor is used to be the system controller. Wind energy is a natural energy available for use, and will not be depleted due to the development of the human. The use of wind energy can be divided into two types, one is mediated by wind energy converted into kinetic energy, such as a windmill, sailing; another one is converted into electrical energy, namely wind power. [7]

Sarkut Ibrahim et.al; [2013]: This paper presents analysis and improvement of power quality (voltage sag, and harmonics) performance of smart grid connected inverter used in distributed generation.The structure of the designed controller consists of outer power with harmonic control loop, middle voltage control loop and inner current control power loop for real and reactive power control in dq reference frame.The developed controller controls the real and Converter). [8]

Hasan Mahamudul et.al; [2013]: This paper speaks to a novel recreation approach of a photovoltaic module with incremental conductance MPPT controlled buck-help converter in the Simulink stage. Numerical conditions connected with the re-enactment procedure have been depicted with the best clarity. This era can likewise be utilized for the recreation of a particular PV module and converter with slightest changing in parameters. [9]

Mamta N. Kokat et.al; [2013]: for high power application, the conventional two-level inverter has many limitations. The Multi-Level Inverter (MLI) began with three level inverter which has been very popular for high voltage and high power applications. The basic concept behind this is to use of series-parallel combinations of power semiconductor switches and DC sources for achieving high power capability. Three levels MLI has three levels which have smoother waveform than conventional, this results in a reduction of harmonics. This work deals with different topologies of three level MLI and SPWM technique to generate switching pattern for three levels and five levels MLI [10].

Gobinath.K et.al; [2013]: This work deals with the improvement of power extracting methods. From solar cells, MLI is used for effectively extracting power. MLI enhance the wave shape of AC output voltage waveform. Seven levels with reduced switches topology are used in this paper. Selective Harmonics Elimination Stepped Waveform (SHESW) technique is used to reduce lower order harmonics which in turn reduces total harmonic distortion (THD). Switches in the inverter are controlled by fundamental switching scheme. Appropriate selection of switching angles gives a reduction of harmonics. 3^{rd} and 5^{th} harmonics are eliminated in this work. This topology reduces initial cost and complexity [11].

T.Salmi, et.al; [2012]: Basic details of PV cell, PV module, PV array and their modeling are studied. Also, the behavior of PV modules at varying environmental conditions like solar irradiation and temperature are studied**.** [12]

Shagar Banu M et.al; [2012]: In this paper, an alternative multi-input rectifier structure is proposed for hybrid wind/solar energy systems. The proposed design is a fusion of the DC to DC converter. The inherent nature of these two converters eliminates the need for separate input filters. The operations of these fused converters are compared with the separate parallel operation of the DC to DC converters. An alternative multi-input rectifier structure is proposed for the hybrid wind/solar energy system. [13]

Joanne Hui et.al; [2012]: In this paper presents the control and modeling of a wind energy system that consists of a single-switch 3-phase boost converter with MPPT technique.The MPPT method in the design is a sensor in nature, which means that the MPPT controller is able to extract maximum power for different wind speeds without using a wind speed sensor. [14]

Shyam B. et.al; [2011]: The small-scale WECS are more efficient and cost effective. Therefore targeted technology development for power quality improvements of small-scale WECSs can make a significant overall contribution toward the national energy supply. [15]

Nagaraj et.al; [2011]: Extracting as much power as possible from the wind and feeding the grid with premium electricity are two main objectives for PMSG generation systems, while obtaining a suitable dc-link voltage is the key to realizing these objectives. The Authors have developed a novel two-phase PMSG - converter system for direct-drive, variable-speed wind turbines, as a new solution to realize the above objectives. [16]

Ma Youjie, et.al; [2010]: Different MPPT techniques, their advantages and disadvantages and why MPPT control is required is explained in. [17]

Carlo Cecati et.al; [2010]: this work deals with a photovoltaic (PV) system with power electronics devices. This paper has two stages: a DC/DC converter and MLI modulated with PWM. The care should be taken due cascading of converters and there may be a problem with MPPT. [18]

Haitham Abu-Rub et.al; [2010]: this work proposed that, getting high efficiency and minimum total harmonic distortion (THD) at switching frequency with medium-voltage (MV) multilevel inverter (MLI). Industries are facing common problems that are effective power quality with increased power rating of switches by minimizing switching frequency. A common remedy is taken into account by increasing the level of an inverter that will give low harmonic distortion at a medium voltage at a low switching frequency which in turn reduces the device losses and increase lifespan of devices [19].

K. Rajambal, et.al: [2006]: The working of PV /Wind hybrid system is understood, different topologies that can be used for the hybridization of more than one system and also about advantages and disadvantages of hybrid system. [20]

CHAPTER- 3

SOLAR-WIND HYBRID ENERGY SYSTEM

3.1 Solar energy

Solar power is the generation of electricity from sunlight. This can be directly obtained from photovoltaic (PV) or indirectly from concentrating solar power (CSP), where the sun's energy is focused on generating power. The evolution of PV cell has a history starting from 18th century.

Photovoltaic System: A photovoltaic system is a system which uses one or more solar panels to convert solar energy into electricity. It consists of multiple components, including the photovoltaic modules, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output.

3.2 Working principle of PV

The photovoltaic effect is a basic physical process through which solar energy is converted into electrical energy directly. The physics of a PV cell or solar cell is similar to the classical p-n junction diode. Solar cells are devices which convert solar energy directly into electricity, either directly via the photovoltaic effect, or indirectly by first converting the solar energy to heat or chemical energy. The most common form of solar cells is based on the PV effect in which light falling on a two layer semiconductor device produces a photovoltage or potential difference between the layers. This voltage is capable of driving a current through an external circuit and thereby producing useful work. [25]

The amount of power available from a solar cell device is determined by

- The type and area of the material.
- The intensity of the sunlight.
- The wavelength of the sunlight

The solar cell consists of two types of material, often p-type silicon and n-type silicon. Light of certain wavelengths is able to ionize the atoms in the silicon and the internal field produced by the junction separates some of the positive charges (holes) from the negative charges (electrons) within the photovoltaic device. The holes are swept into the positive or p-layer and the electrons are swept into the negative or n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier. As shown in Figure 3.1, power can be produced from the cells under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

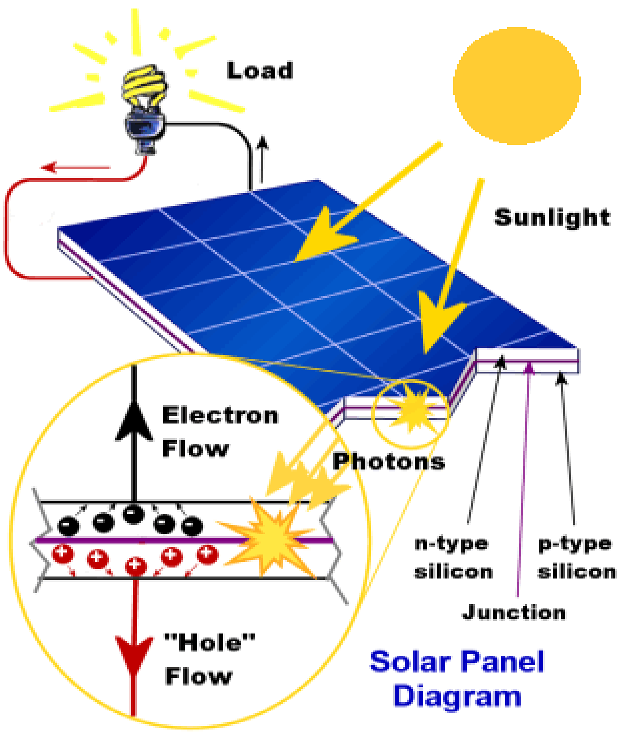


Figure 3.1: Schematic diagram of solar panel

Solar cells in the market can be classified into two main categories - crystalline silicon cells and thin-film cells. Crystalline silicon cells can be further divided into monocrystalline cells (Efficiency: 15-18%) and poly-crystalline cells (Efficiency 13-16%). Thin-film cells include the amorphous silicon cells (Efficiency 5-8%), copper indium diselenide cells (CIS) (Efficiency 7.5-9.5%) and cadmium-telluride cells (CdTe) (Efficiency 5-8%). [25]

The performance of a solar cell is expressed in terms of its energy conversion efficiency, i.e. the efficiency in converting the energy in sunlight into electricity. The earliest silicon solar cells had efficiencies of just a few %. Nowadays commercial solar cells can approach almost 20% in efficiency, while special-made cells and experimental cells can exceed 30%. For the majority of applications, multiple solar cells need to be connected in series or in parallel to produce enough voltage and power. Individual cells are usually connected into a series string of cells to achieve the desired output voltage. The complete assembly is usually referred to as a module and manufacturers basically sell modules to customers. An array is a structure that consists of a number of PV modules, mounted on the same plane with electrical connections to provide enough electrical power for a given application. Arrays range in power capacity from a few hundred watts to hundreds of kilowatts. The connection of modules in an array is similar to the connection of cells in a single module.

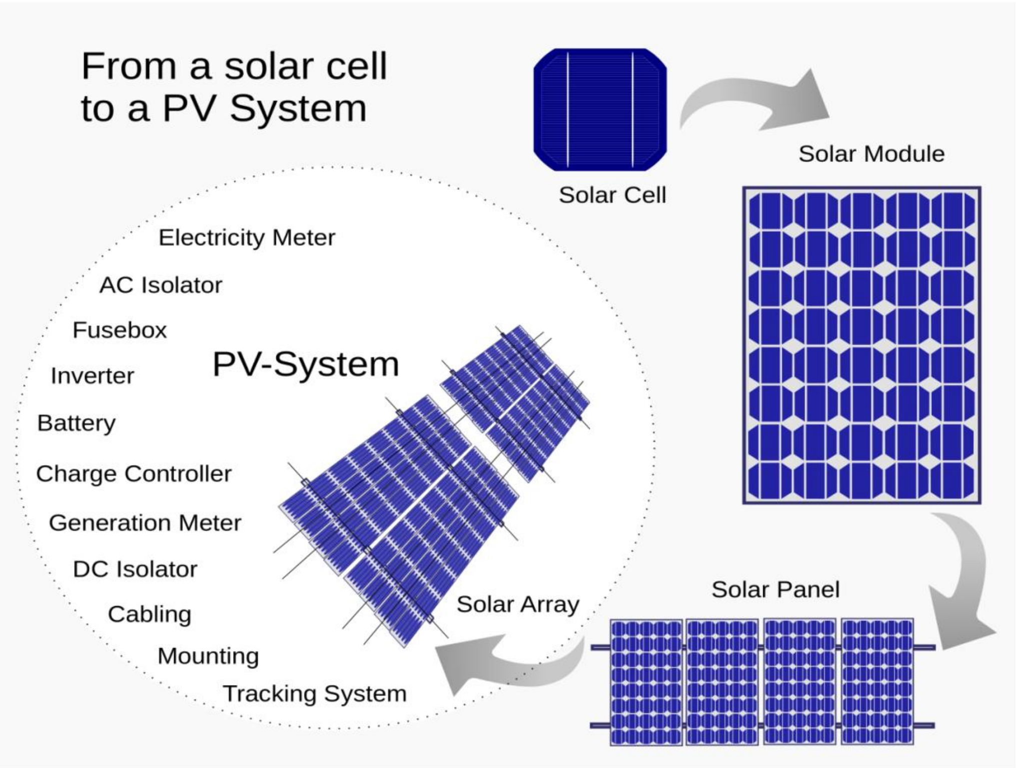


Figure 3.2: PV cell, PV module & PV array

To increase the voltage, modules are connected in series and to increase the current they are connected in parallel. Matching is again very important for the overall performance of the array. The formation of the cell to the module to the array is shown in Figure (3.2).

3.3 Photovoltaic arrangements

A photovoltaic energy system is mainly powered by solar energy. The configuration of PV system is manifested in figure (3.3).

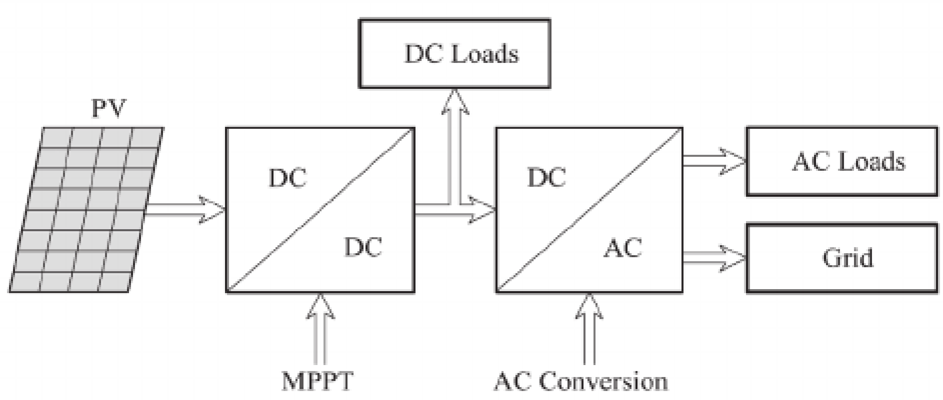


Figure 3.3: Block diagram of PV energy system.

3.3.1 Photovoltaic cell

PV cells are made of semiconductor materials, such as silicon. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material.

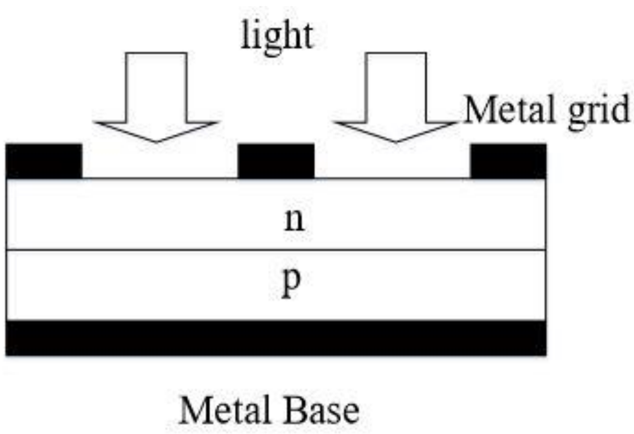


Figure 3.4: Structure of PV cell.

If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current - that is, electricity. This electricity can then be used to power a load. A PV cell can either be circular or square in construction.

3.3.2 Photovoltaic module

Due to the low voltage generated in a PV cell (around 0.5V), several PV cells are connected in series (for high voltage) and in parallel (for high current) to form a PV module for desired output. Separate diodes may be needed to avoid reverse currents, in the case of partial or total shading, and at night. The p-n junctions of mono-crystalline silicon cells may have adequate reverse current characteristics and these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels.

3.3.3 Photovoltaic array

The power that one module can produce is not sufficient to meet the requirements of home or business. Most PV arrays use an inverter to convert the DC power into alternating current that can power the motors, loads, lights etc. The modules in a PV array are usually first connected in series to obtain the desired voltages; the individual modules are then connected in parallel to allow the system to produce more current.

3.4 Characteristics of PV cell

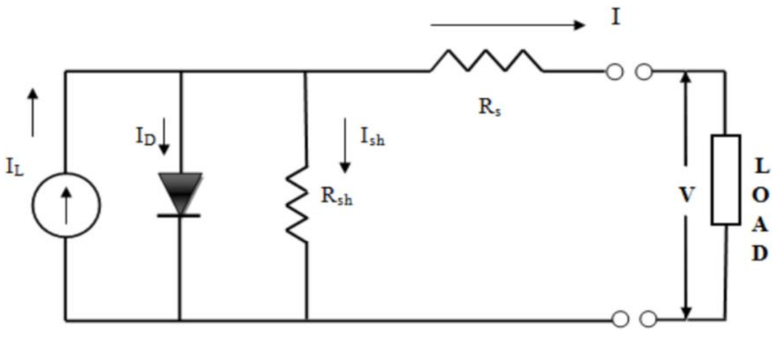


Figure 3.5: Equivalent circuit of a PV cell

An ideal is modeled by a current source in parallel with a diode. However, no solar cell is ideal and thereby shunt and series resistances are added to the model as shown in the PV cell diagram above. RS is the intrinsic series resistance whose value is very small. R_p is the equivalent shunt resistance which has a very high value.

Applying Kirchoff's law to the node where I_{ph}, diode, R_p and R_s meet, we get

$$\mathbf{I_{ph} = I_D + I_{Rp} + I} \qquad \text{……….. (3.1)}$$

We get the following equation for the photovoltaic current:

$$\mathbf{I = I_{ph}\text{-}I_{Rp}\text{-}I_D} \qquad \text{……….... (3.2)}$$

$$\mathbf{I = I_{ph} – I_o.[exp(V+I*R_s/V_T) – 1] – [V+I*R_s/R_p]} \qquad \text{……….. (3.3)}$$

Where,

I_{ph} = Insolation current, I = Cell current, V = Cell voltage, I_0 = Reverse saturation current,

R_s = Series resistance, R_P = Parallel Resistance, V_T = Thermal voltage (KT/q),

K = Boltzman constant, T = Temperature in Kelvin, q = Charge of an electron.

3.4.1 Efficiency of PV cell

The efficiency of a PV cell is defined by the ratio of peak power to the input of solar power.

$$\mathbf{\eta = V_{mp}.I_{mp}/I\ (KW/m^2)*A\ (m^2)} \qquad \text{………. (3.4)}$$

Where,

V_{mp} = voltage at peak power, I_{mp} = Current at peak power,

I = Solar intensity per square meter, A = area on which solar radiation fall.

The efficiency will be maximum if we track the maximum power from the PV system at different environmental condition such as solar irradiance and temperature by using different methods for maximum power point tracking. I-V and P-V characteristics of PV module are shown in figure (3.6).

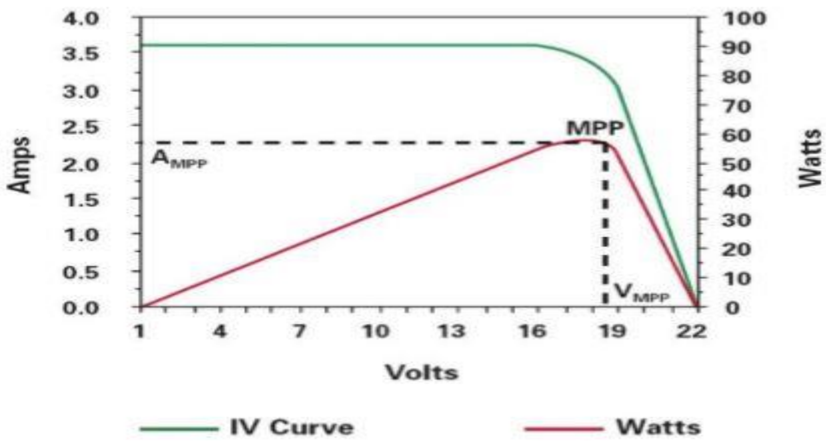


Figure 3.6: IV & PV characteristics.

3.5 Wind energy

The Wind is a free source of power and it is available everywhere. Always the wind flows from a higher atmospheric pressure region to the lower atmospheric pressure region due to the non-uniform heat by the sun and due to the rotation of the earth. In other words, it can be said that the wind is a form of solar energy available in the form of the kinetic energy of air.

Wind energy can be transformed into many forms of energy, such as the wind is used to generate electricity; windmills are also used to lift water pump turbines and propelling vessels. The Wind have a good amount of energy in it and whatever amount of power obtained from the wind is much greater than the power available from other sources which are used by humans.

3.5.1 System configuration

This system comprises of a wind turbine which transforms wind's kinetic energy into rotating motion, a gear box to match the turbine speed to generator speed, a generator which converts mechanical energy into electrical energy, a rectifier which converts ac voltage to dc, a controllable dc-dc converter to track the maximum power point and an inverter which converts dc voltage to ac. The schematic diagram of the wind energy system is manifested in the figure below.

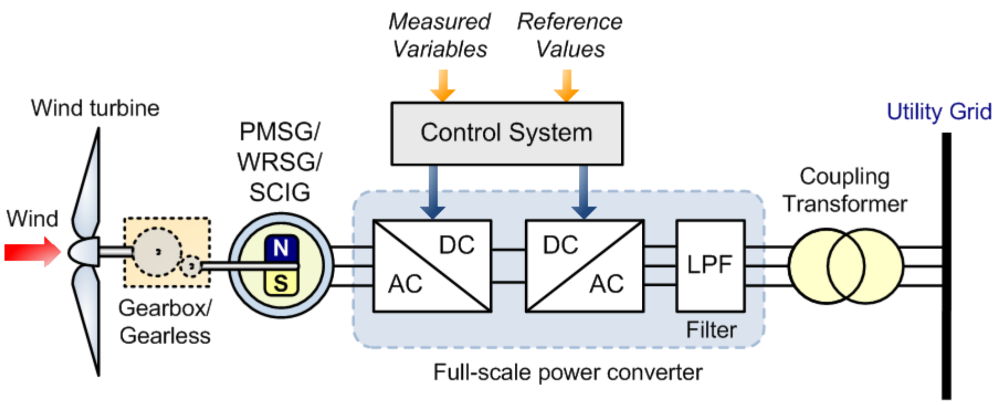


Figure 3.7: Schematic diagram of wind energy system

The turbine should be developed with two blades or three blades which have the higher efficiency to collect more wind power [24]. Higher speed and more efficient turbines were necessary electricity generation.With the help of wind power, wind turbine generator electricity by driving an electrical generator. By using the power of the wind, wind turbines produce electricity by drive an electrical generator. The Wind produces a driving force to the blades while passing over it which drive the generator.

A shaft connected to blades and shaft will rotate when blades are rotating and gear box is connected to the shaft. The gearbox helps to adjust the rotational speed which is favorable or suitable for the generator at the speed where the appropriate output is obtained. The obtained power from the wind generator is transferred to the transformer which steps up generated voltage. Wind energy can be defined as the kinetic energy of the air mass flowing per unit time.

$$P_0 = \frac{1}{2}(\text{air mass per unit time}) * (\text{Wind Velocity})^2 \quad \text{………..} (3.5)$$

$$P_0 = \frac{1}{2}(\rho A V w) * (V w)^2 \quad \text{………..} (3.6)$$

The above equation is for power available in the wind, but it is not similar with whatever power is transferred through a wind turbine. The power available and the power transformed is different by the factor of power coefficient. So the power generated aerodynamically because of wind turbine is given by

$$P_0 = 0.5(\rho A V w) * (V_W)^2 \quad \text{..……….} (3.7)$$

Where,

ρ = air density (Kg/m3), a =Swept area of the wind turbine

V_W =Wind Speed (m/s), C_P= Coefficient of Power

The Wind turbine is moreover dependent on the velocity of the wind. According to Indian geographical conditions nobody can expect constant wind flow.

During soft start fluctuations occurred, and due to change in the direction of the flow of wind, the revolution speed also changes. Due to the fluctuation occur in the flow of air, the output voltage is also distributed so to attain desired output, we have to boost the voltage and get constant output.

3.5.2 Generator

The shaft of the wind turbine is mechanically coupled to the rotor shaft of the generator so that the mechanical power developed by the wind turbine (by kinetic energy to mechanical energy conversion) is transmitted to the rotor shaft. This rotor structure has a rotor winding (either field or armature). In both the cases, we get a moving conductor in a stationary magnetic field or a stationary conductor in moving the magnetic field. In either case, an electric voltage is generated by the generator principle.

3.5.2.1 Permanent magnet synchronous generator

A synchronous machine generates power in large amounts and has its field on the rotor and the armature on the stator. The rotor may be of salient pole type or cylindrical type.

In the permanent magnet synchronous generator, the magnetic field is obtained by using a permanent magnet, but not an electromagnet. The field flux remains constant in this case and the supply required to excite the field winding is not necessary and slip rings are not required. All the other things remain the same as a normal synchronous generator.

The EMF generated by a synchronous generator is given as follows

$$\mathbf{E = 4.44 * f * \varphi . t} \qquad \text{......... (3.8)}$$

Where,

f= Frequency,

φ = Flux,

t = No. of turns.

3.5.3 MPPT of wind power

Wind power versus wind speed characteristics of wind power system is shown in fig below

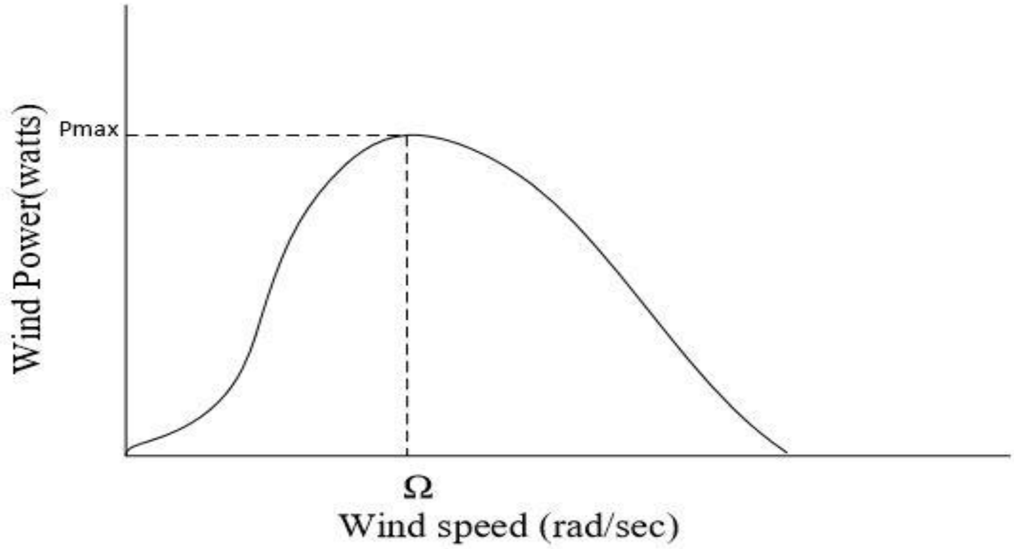


Figure 3.8: Power vs. speed characteristics of the wind turbine.

At maximum power point

$$\frac{dP}{d\Omega} = 0 \qquad \text{………. (3.9)}$$

From chain rule

$$\frac{dP}{d\Omega} = \frac{dP}{dD} * \frac{dD}{dVw} * \frac{dVw}{d\Omega e} * \frac{d\Omega e}{d\Omega} \qquad \text{..……. (3.10)}$$

Where,

P = Wind power, **Ω** = Rotor Speed, Ω_e = Generator phase voltage angular speed,

V_W = Rectifier output voltage, D = Duty cycle of converter.

3.5.4 Operation

If the wind is too high, from that the wind turbine has to be protected, if wind speed is too high then gearbox would suffer from high stress with extracting the appropriate power to stausfy the load. Ought to this, the generator will be overloaded and may be burned. Strategy to control the wind turbine is clear. From this graph, it is shown that at very low wind speed, it unable to generate power so to generate energy, wind should be at cut in speed. Below this cut in speed the turbine will not start or rotate. It depends on the design and manufacturer that with wind speed less than the desired speed then turbine may rotate but can not generate electricity or may happen they didn’t rotate [21].

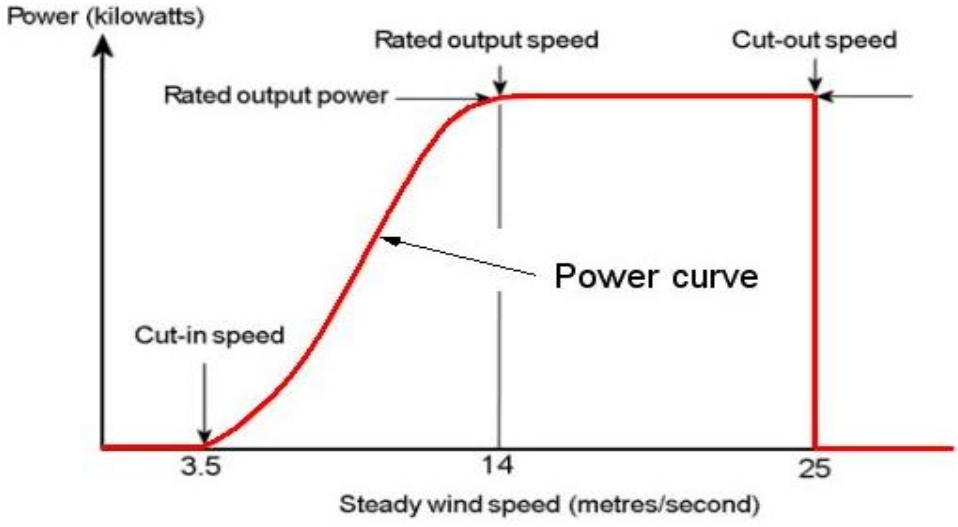


Figure 3.9: Wind turbine graph for cut in speed

If the wind speed is too high, for the protection of wind turbine, WECS have to engage protection mechanism and cannot allow the wind turbine to rotate or stop it because if it does not then the stress is so high and may wind turbine brake so at this time wind turbine stop.

3.5.5 Three fundamental things in wind:

1) **Yaw control:** It is essentially the means of orienting the wind turbine, as it turns in the direction of the wind. If we use Yaw as control mechanism then we have to make it all the time move. There are two types of wind flow:

a) **Downstream wind flow:** In this, downstream wind turbine there is no need of Yaw control because it automatically turns, but here disadvantage is a tower, as the maximum wind will be wasted due to the tower.

b) **Up stream wind flow:** In this, there is a need to control the Yaw control.

2) **Solidity:** Solidity is defined as the ratio of the projected blade area to the area of the wind intercepted. The projected blade area is equal to the area projected in the direction of the wind. With torque and speed, solidity has a direct relationship. High solidity rotors are suitable for pumping water because it has high torque and low speed. Low solidity rotors are suitable for electrical power generation because it has high-speed and low torque.

3) **Tip speed ratio:** TSR of a wind turbine can be express that

$$\lambda = W_T R/Vw \qquad \text{……….. (3.11)}$$

Where,

λ= Non-dimensional

W_T= Rotational Speed of turbine

R= Radius of turbine

Vw= Wind Speed (m/s)

3.5.6 Modern wind turbine

A wind turbine is a machine which converts the power from the wind into electricity. The principle of the windmill is to converts the kinetic energy of the wind to mechanical energy and further, it converts mechanical energy into electrical energy. Wind turbines are connected to generators. When turbine rotates, generator rotates and electricity produces and these are connected to power grid. These networks may or may not be connected to the power grid. In terms of the small scale basis, the wind turbine is actually quite small up to the capacity of 10KW or less. In terms of total production capacity, the turbines that make up the Most of the capacity are generally quite large - of the order of 500 kW to 2 MW. These larger turbines are used mainly in major public service networks, primarily in Europe and the United States. Typical modern wind turbines are connected to an interconnected grid. [17]

3.5.6.1 Horizontal axis wind turbine

The Horizontal Axis Wind Turbine (HAWT). In other words, the axis of rotation is parallel to the ground. HAWT rotors are usually classified according to the orientation of the rotor (Facing the wind or downwind of the tower), the hub design (rigid or staggered), the control rotor (pitch vs. stall), the number of blades (usually two or three blades), and how they are aligned with the wind (free or active yaw).

The major subsystems of a typical horizontal axis wind turbine including [15]

1) The rotor constituted by the blades and the support hub.

2) The driving mechanism, which has rotating parts of the WT (excluding rotor); it generally has Generator, Shafts, Gearbox, Coupling, and Mechanical Brake.

3) Mainframe, including the nacelle of a wind turbine, bed plate, and yaw mechanism.

4) The tower and foundation.

5) The Controlling of the machine.

6) The balance of the electricity system including, Transformers, Switchgear, Cables, and Electrical power converters.

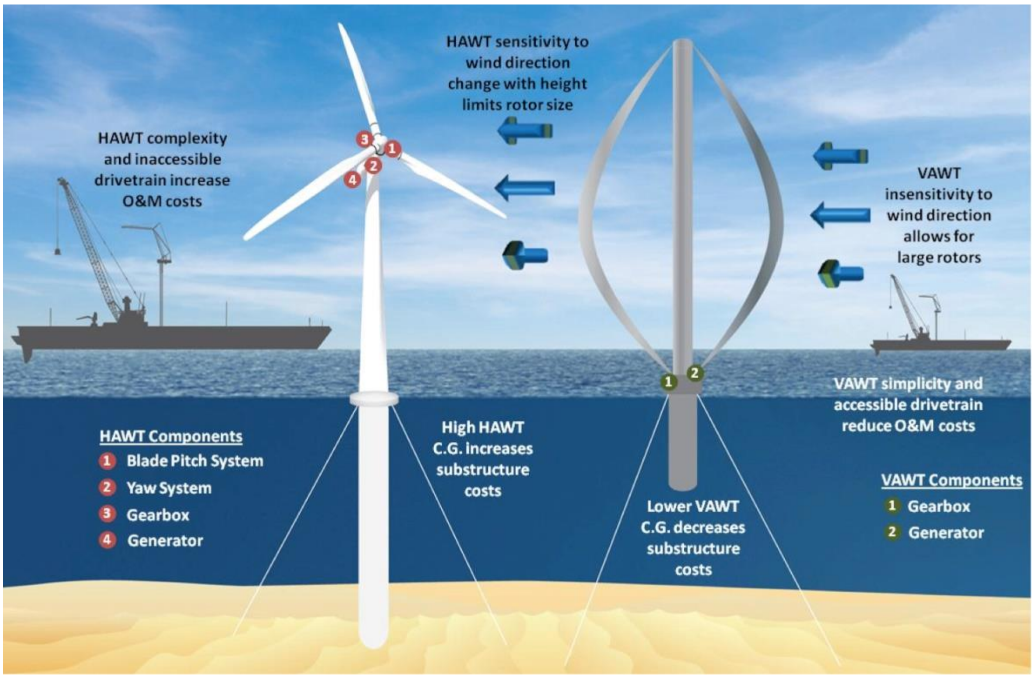


Figure 3.10: HAWT and VAWT

Advantages

a) Variable pitch angle gives the best angle of attack.

b) To obtain more efficiency, the blades always rotate perpendicularly to the flow of wind and it receives power from the rotation.

Disadvantages

a) Transportation is difficult due to 90 meters long blades and tall towers. 20% of equipment costs are occupied by transportation.

b) At high installation of HAWT's are difficult. It requires very large and expensive cranes and skilled person.

c) To support the heavy Blades, Gearbox, and Generators robust tower construction is required.

d) HAWT's require additional yaw control mechanism for the rotating of blades.

3.5.6.2 Vertical axis wind turbine

In VAWT's the rotor is mounted on a vertical axis, the arrangement of these types of turbine does not require pointed wind force. So, these can be easily used where the wind speed is variable all the times. In Vertical axis turbine, the tower does not need a large investment to support turbine blades because gearbox and the generator are located near the ground.

Advantages

- **a)** This tower structure is less frequently used.
- **b)** It doesn't require any fixed pitch rotor designs mechanisms.
- **c)** VAWT's generally they start generating below 10m/s wind speed.
- **d)** Low noise, Low maintenance cost.

Disadvantages

- **a)** The single blade will work at a time so efficiency is very low.
- **b)** They produce pulsating torque.
- **c)** They have relatively high vibration because the airflow nears the ground so, they create high turbulence flow.
- **d)** They create noise pollution.
- **e)** They need an initial push to start, this action uses few of its own produce electricity.

3.6 Hybrid energy system

Hybrid energy is a combination of two or more energy sources for producing electricity. There are many sources of combining renewable energy sources to produce power but the very common combination is biomass- wind fuel cell and photovoltaic - the wind. The hybrid energy sources can help farmers to run their tube wells to provide water to their irrigation land. Combining two or three energy sources to form one combinational source is capable of generating efficient energy to power a house or a small industrial unit.

Nevertheless, different renewable energy sources can complement each other, multisource hybrid alternative energy systems have great potential to provide higher quality and more reliable power to customers than a system based on a single resource. Because of this, hybrid energy systems have caught worldwide research attention. There are many combinations of different alternative energy sources and storage devices to build a hybrid system. Due to natural intermittent properties of the wind and photovoltaic power, stand-alone wind and/or PV renewable energy systems normally require energy storage devices or some other generation sources to form a hybrid system. Solar panels are too much costly and the production cost of power by using them is generally higher than the conventional process, it also not available in the night/on cloudy days, similarly, Wind turbines can't operate in high or low wind speeds.

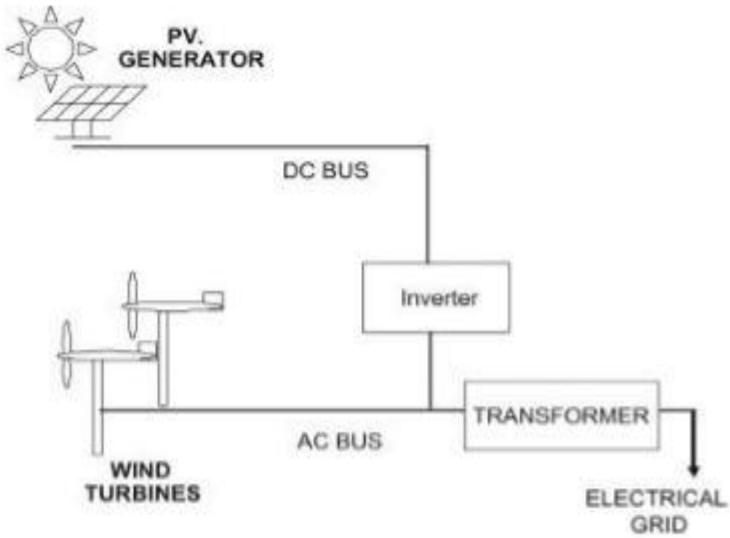


Figure 3.11: Proposed hybrid system.

If these renewable sources are combined into one hybrid power generating system the drawbacks discussed can be avoided partially/completely, depending on the control units. As the one or more drawbacks can be overcome by the other sources hybrid generation is becoming a trend in DGs. In this study Wind and the Solar, combination is considered as hybrid study and estimation of new PV plant with the existing wind farm is proposed.

Figure 3.11 shows the system configuration for the proposed hybrid alternative energy system. This system can be considered as a complete "green" power generation system because the main energy sources are environmentally friendly. However, when connected to a utility grid, operation and performance requirements, such as voltage, frequency, and harmonic regulations, are imposed on the system.

Advantages:

- **Eco-friendly;** it is clean energy and it doesn't emit green house gases which cause degradation of air and acid rain as well.
- **Renewable resource;** it will not exhaust or deplete over the year. It doesn't have cost of fuel.
- Reliablity.
- Leads to employement.
- Boosts public health.
- Less maintainence of facilities.

Disadvatages:

- The electricity generation capacity is still not large enough.
- Low efficiency levels
- Require a huge upfront capital outlay.

CHAPTER 4

RESEARCH METHODOLOGY

Hybrid renewable energy sources becoming more interested area of research because it is a combination of two or more renewable energy sources. It also helps to supply electricity to the load where power transfer from conventional plant is not possible. This dissertation proposes a grid connected hybrid system which comprises of PV plant and Wind farm. Simulation of PV plant is done by the use of MATLAB 2016a. Boost converter is used to boost up the output voltage of PV array and the controlling of switch of boost converter is done by the use of MPPT technique (Incremental Conductance). The THD content present in the voltage and current at the AC side of inverter is reduced using five level inverter. Enhancement of power quality is the main aim of this dissertation work; therefore, it uses Power Conditioning System (PCS) in wind farm. It is very well known that the PCS has rectifier and inverter to condition the incoming power. But in this work MPPT is also used in between rectifier and inverter to boost up the output voltage of rectifier. MLI is used here to reduce THD content present in output waveform.

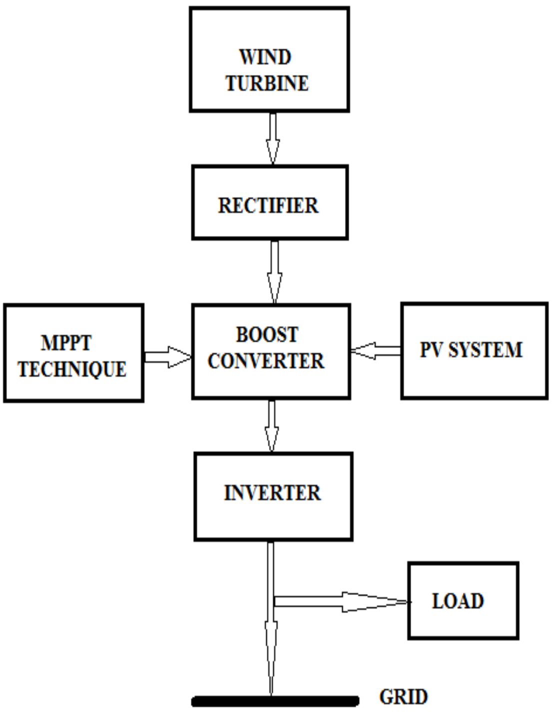


Figure 4.1: Flow chart of PV-wind hybrid system.

CHAPTER-5

POWER ELECTRONICS DEVICES & CONTROL STRATEGY

5.1 Basic switching devices

SCR was first introduced in 1957 as power semiconductor devices. A great variety of solid state devices is available in the market. Some of the most commonly used devices are as follows:

a) Diodes: These are uncontrolled rectifying devices.

b) Thyristors: These are controlled by turning ON and OFF by the gate signal.

c) Controllable Switches: These turn ON and OFF by controlling signals.

For a specific application, the choice depends on the power, voltage, current and the condition of the system frequency. A common feature of these devices is that all devices are three-terminal as shown in their circuits symbols generally used.

5.2 AC to DC rectifier

In the previous years, according to particle physician point of view, the output of the ideal power converter should be the best direct current supplied to the load. The best direct current means that it should have very low ripple content in it and very high stability. So the main aim of the researchers has become to get the best direct current. They are doing it by increasing the number of pulses of a rectifier which reduces the dc ripple content from dc current. In previous years, the rectifier was uncontrolled because they were using a diode for making the DC to AC and diode is an uncontrolled device. The basic principle of the diode is that it works when the forward bias voltage is applied to it. It doesn’t require any control signal to on or off. By the invention of the thyristor, a new area of research has made. The thyristor is a controlled device means it requires some signal to turn on and turn off. When thyristors are used instead of diode the rectifier is known as a controlled rectifier. Thyristors require commutation circuit also.

5.2.1 three-phase six-pulse diode bridge rectifier

In a diode bridge rectifier, pulses present in output waveform is equal to the twice of a number of phases, i.e., p=2m, where p is the number of pulses and m is a number of phases. Diodes are always rated by their peak inverse voltage (PIV). PIV of diode used in bridge rectifier is equal to the half of PIV of diode used in star rectifier. In high power applications, a three phase bridge rectifier is used. It doesn't require a transformer for applying AC voltage to the bridge. The transformer may or may not be used with diode bridge rectifier. It has less ripple content in comparison to the half and full wave diode bridge rectifier [25]. It has three legs and each leg has two diodes connected in series. The upper diodes work in the positive half cycle and lower diodes work in the negative half cycle. Therefore, they named as positive and negative group respectively. The numbering of diodes is done as the conduction sequences. Fig. 4.4 shows the configuration rectifier. D_1, D_3 and D_5 belong from positive group and D_2, D_4 and D_6 belong from the negative group. Each diode conducts for 120^o. In a group, a diode conducts after 120^o to another diode either in the positive or negative group. In a single leg, the negative diode conducts after 180^o to the positive diode [24].

The equivalent circuit diagram of the three-phase six-pulse diode rectifier showed. The average DC output voltage of this circuit is given by the following:

$$V_{DC}=3\left(\frac{3\sqrt{2}}{\Pi}\right)*VL*cos\alpha \qquad \text{………..} \ (5.1)$$

Where

V_L= line-to-line voltage on three-phase AC side of the rectifier

α= angle of firing delay in the switching.

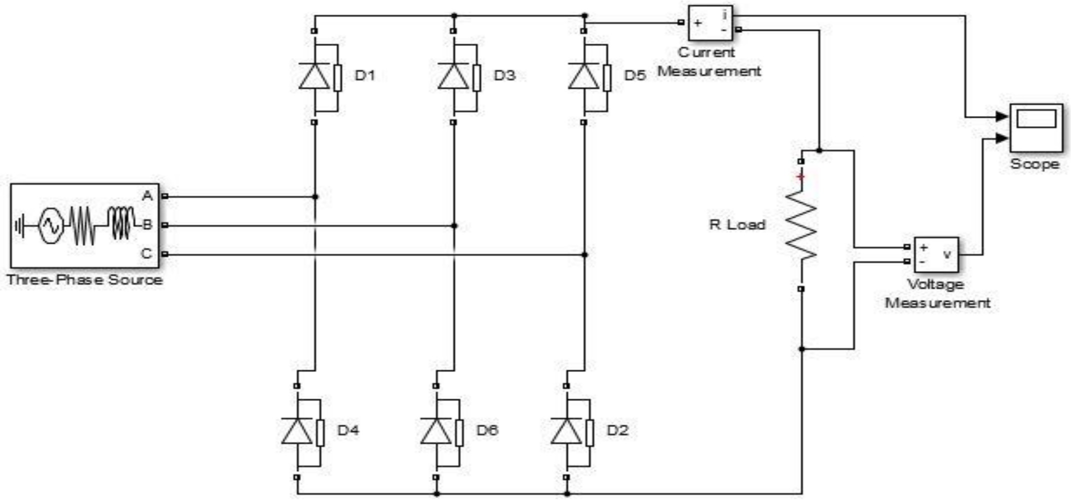


Figure 5.1: diagram of three-phase six pulse rectifier.

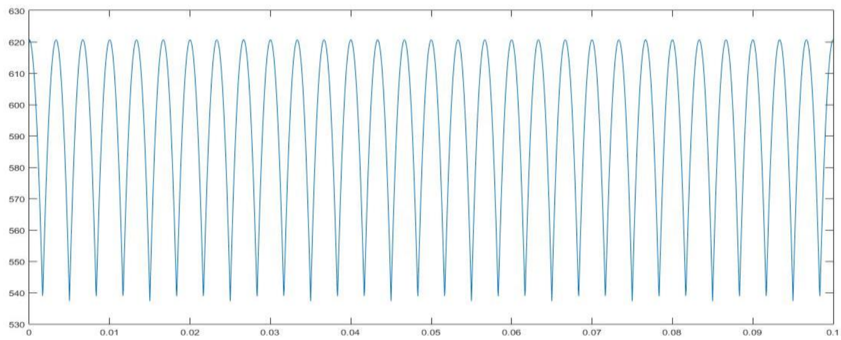


Figure 5.2: Output voltage of three-phase six pulse rectifier.

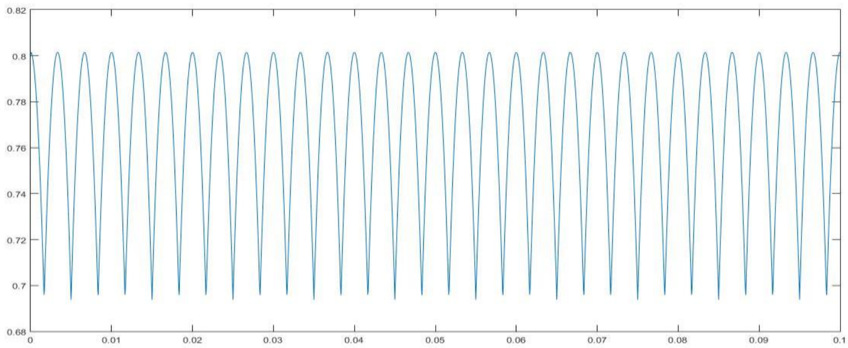


Figure 5.3: Output current of three-phase six pulse rectifier.

5.3 Multi-level inverter

MLI have attracted many utilities and power industries because of their use and advantages. It is well suited for reactive power compensation. It can work with high voltage and high power application with the use of IGBTs. It produces voltage waveform in shape of staircase. The level of voltage is dependent on the number of DC voltage sources are used. Harmonic content present in the voltage waveform decreases with the increase in DC voltage sources [25]. The upcoming topologies of MLI must have these things which are given below:

a) Less switching devices as much as possible.
b) Lower switching frequency.
c) Capable of withstanding with very high power and voltage application.

5.3.1 Types of MLI

1) Diode-clamped MLI (DCMLI)
2) Flying-capacitor MLI (FCMLI)
3) Cascade MLI (CMLI)

5.3.1.1 Cascade MLI

Cascade MLI contains single phase full bridge inverter which is also known as H-bridge inverter. Single H-bridge has only three-level of the output voltage from peak to peak. A number of H-bridge increase with the increase in the level of the output voltage and they are connected in series. Every H-bridge contains one separate DC sources (SDCS) which can be taken from the fuel cell, solar cell or batteries [25]. The AC terminal of each H-bridge is connected in series. Cascade H-bridge does not require any clamping diodes for clamping or capacitors for voltage balancing. An m-level of cascade MLI is shown below, which has (m-1) SDCS and H-bridge. It also can be used for reactive power compensation [25].

Advantages:

1) The level of the output voltage is twice the number of SDCS ($m=2N_s+1$, where N_s is the number of bridges).
2) It is cheaply and less complex in comparison to DCMLI and FCMLI.
3) To reduce the switching losses and stresses on the device, soft switching can be done.

Disadvantages:

1) For active power conversion, SDCS is required.

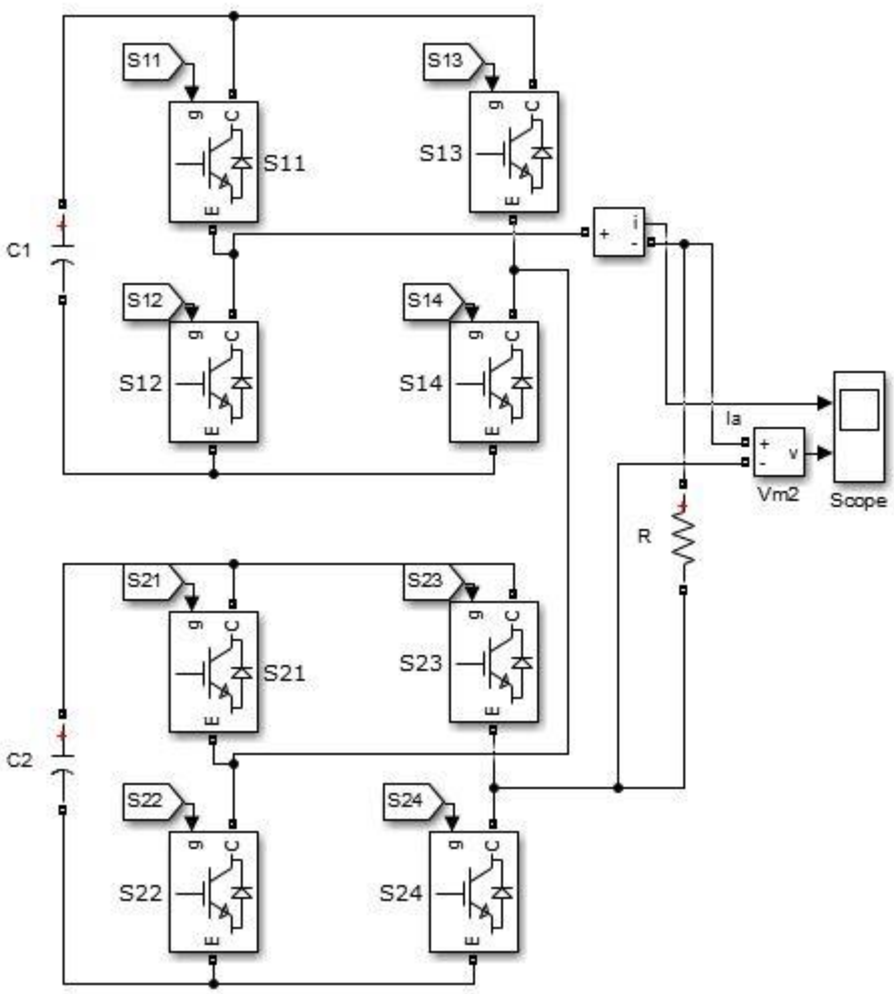


Figure 5.4: Five level cascade MLI.

5.4 DC-DC converter

The dc-dc converter is an electrical circuit whose main application is to transform a dc voltage from one level to another level. It is similar to a transformer in AC source, it can able to step the voltage level up or down. The variable dc voltage level can be regulated by controlling the duty ratio (on-off time of a switch) of the converter. [25]

There are various types of dc-dc converters that can be used to transform the level of the voltage as per the supply availability and load requirement. Some of them are discussed below.

1. Buck converter

2. Boost converter

3. Buck-Boost converter.

5.4.1 Boost converter

The functionality of boost converter is to increase the voltage level. The circuit configuration of the boost converter is manifested in figure (5.5).

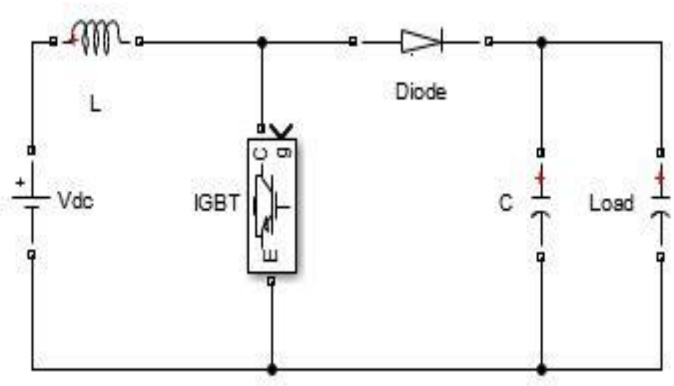


Figure 5.5: circuit diagram of boost converter

The current carried by the inductor starts rising and it stores energy during ON time of the switching element. The circuit is said to be in charging state. During OFF condition, the reserve energy of the inductor starts dissipating into the load along with the supply. The output voltage level exceeds that of the input voltage and is dependent on the inductor time constant. The load side voltage is the ratio of source side voltage and the duty ratio of the switching device. [25]

5.5 Control strategy

Controlling strategies used in PV-wind hybrid system:

- Pulse Width Modulation.
- Maximum Power Point Tracking.

All these functions are performed with the help of power electronics devices in the solid state periodically on and off at the desired frequency. In terms of applications, no other technology has brought a big change in power engineering or holds greater potential for improvement in the future, the power electronic devices & circuits. In this chapter, we examine the power electronic circuits used in modern wind and photovoltaic energy systems.

5.5.1 Pulse width modulation-

Basically, the pulse width modulation is used for the controlling process with constant amplitude pulses. Ideal PWM waveform has zero rise time and fall time. In this time, the majority of the electronic and electrical devices have power electronic circuits and they are controlled by PWM signals. Fast switching of power electronic devices depends upon the fast rising and falling time which minimizes switching transition time and switching losses [24]. The output voltage of the inverter is controlled by controlling the width of pulses. Reduction of harmonic content present in the inverter output voltage is depending upon the width of pulses. There are so many PWM techniques but here only three techniques are given:

a) Single-pulse modulation
b) Multiple-pulse modulation
c) Sinusoidal-pulse modulation.

PWM inverters require forced commutation. Above three techniques are different from each other by their output voltage and harmonic content present in that. Therefore, the choice of PWM technique is to depend upon that which type of output voltage is needed and how much harmonic content should present in the output voltage waveform [24].

5.5.1.1 Sinusoidal pulse-width modulation (SPWM) - The MPM technique has disadvantages that it has equal pulse width over a cycle. To overcome this, SPWM technique has come into the picture. SPWM technique also has several numbers of pulses per half cycle as MPM but with different pulse width. In SPWM technique, firing pulses are generated by comparing the sinusoidal reference signal with the high-frequency triangular carrier signal. Modulation index (MI) is the ratio of the amplitude of reference signal and amplitude of carrier signal. MI can’t be more than unity. If MI is less than one then the number of pulses per half cycle is increased in comparison to the MI is greater than one [24].

Controlling strategy of five levels is shown below:

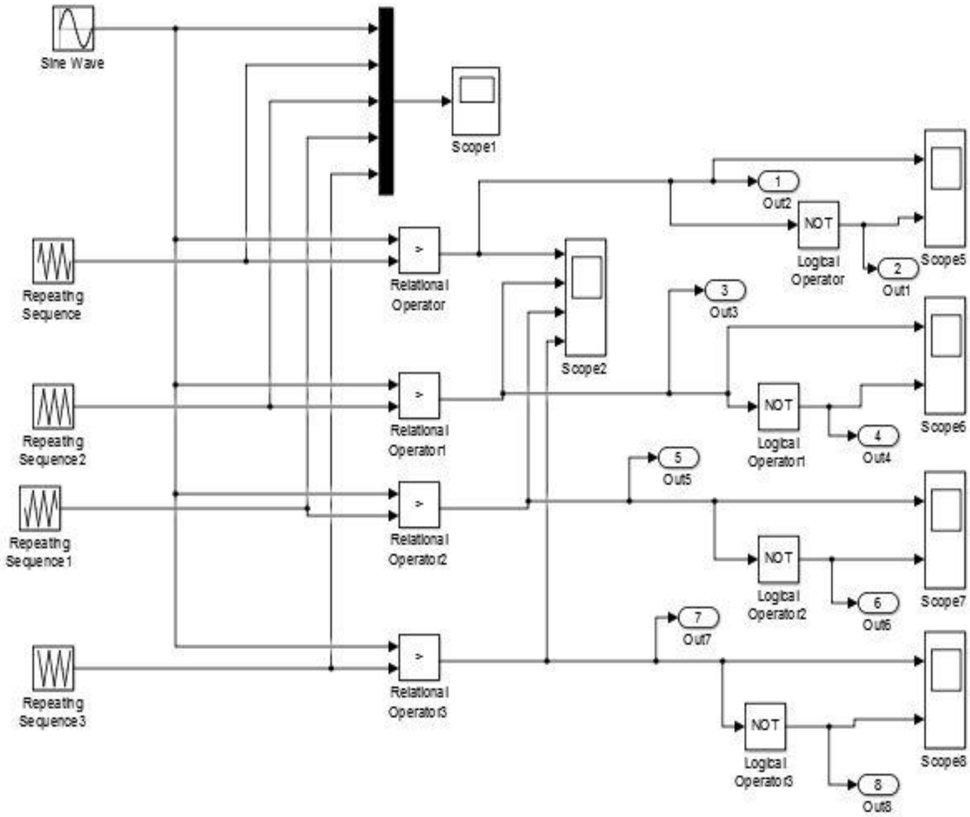


Figure 5.6: Controlling strategy of five level cascades MLI [$_{matlab}$].

Comparison of the reference signal and the carrier signal is shown below:

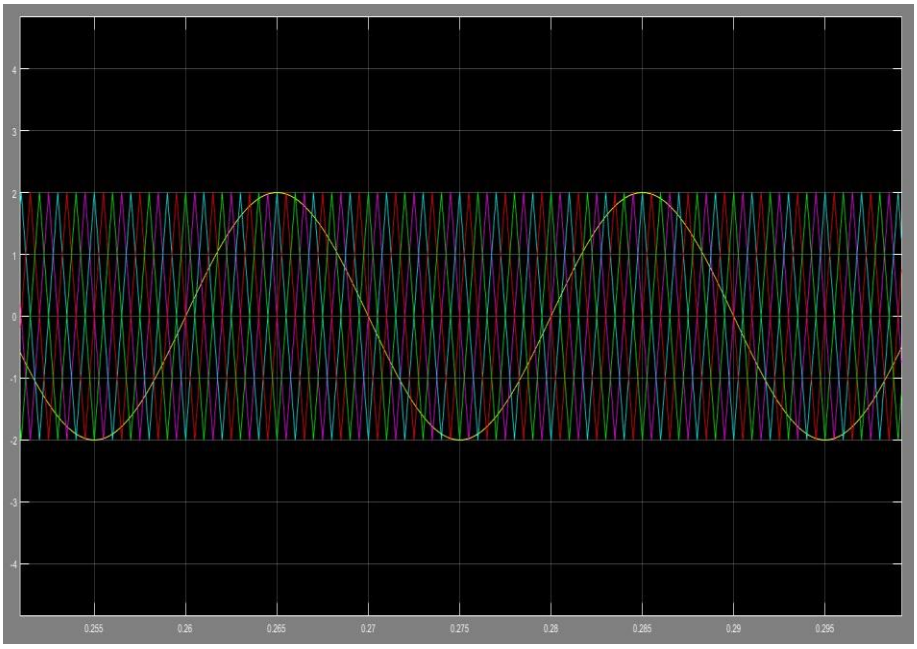


Figure 5.7: Comparison of reference signal and carrier signal.

5.5.2 Maximum Power Point Tracking (MPPT)

5.5.2.1 An overview of maximum power point tracking

Maximum Power Point Tracking frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. MPPT is not a mechanical tracking system that "physically moves" the modules to make them point more directly at the sun. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Additional power harvested from the modules is then made available as increased battery charge current. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different [20]. A typical solar panel converts only 30 to 40 % of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel. According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence our problem of tracking the maximum power point reduces to an impedance matching problem. In the source side, we are using a boost converter connected to a solar panel in order to enhance the output voltage so that it can be used for different applications like a motor load. By changing the duty cycle of the boost converter appropriately we can match the source impedance with that of the load impedance.

The equation (5.2) has defined the efficiency of the algorithms, where Pact is the product of current and voltage at the output of the wind turbine when the simulation is carried out under desired operating conditions. The power obtain is maximum obtained from wind turbine theoretically which is P_{max}.

$$\eta = (P_{act}/ P_{max})*100 \qquad \text{............ (5.2)}$$

5.5.2.2 Different MPPT techniques

There are different techniques used to track the maximum power point. Few of the most popular techniques are: [20]

I. Perturb and Observe (hill climbing method)
II. Incremental Conductance method
III. Fractional short circuit current
IV. Fractional open circuit voltage
V. Neural networks
VI. Fuzzy logic

The choice of the algorithm depends on the time complexity the algorithm takes to track the MPP, implementation cost and the ease of implementation.

5.5.2.2.1 Incremental conductance

Incremental conductance method uses two voltage and current sensors to sense the output voltage and current of the PV array. The P&O method has limitation to track the peak power under fast varying wind speed condition. This problem is overcome by Incremental Conductance (IC) technique. The IC method stops perturbation at the operating point when MPPT has reached the Maximum Power Point. Perturbation can be calculated using dl/dV and –I/V when above condition is not fulfilled. This relationship comes from the fact that, when MPPT will be right to the MPP then dP/dV will be negative conversely it will be positive when MPPT will be left to the MPP. The IC technique has benefits over P&O because it has disadvantaged that, it oscillates across MPP. Also, the variation in wind speed can be tracked quickly by IC with higher accuracy than P&O but it increases the complexity as compare to P&O.

$$\mathbf{P = V*I} \qquad \text{………….. (5.3)}$$

Differentiating with respect to voltage gives;

$$\frac{dP}{dV} = \frac{d(V*I)}{dV} \qquad \text{…………. (5.4)}$$

$$\frac{dP}{dV} = I + V * \left(\frac{dV}{dV}\right) \qquad \text{………….. (5.5)}$$

$$\frac{dP}{dV} = I * \left(\frac{dV}{dV}\right) + V * \left(\frac{dI}{dV}\right) \qquad \text{………….. (4.6)}$$

$$\frac{dP}{dV} = 0 \quad \text{………..} (5.7)$$

$$I+V*\left(\frac{dI}{dV}\right) = 0 \quad \text{..……… } (5.8)$$

$$\left(\frac{dV}{dV}\right) = -\frac{I}{V} \quad \text{………..} (5.9)$$

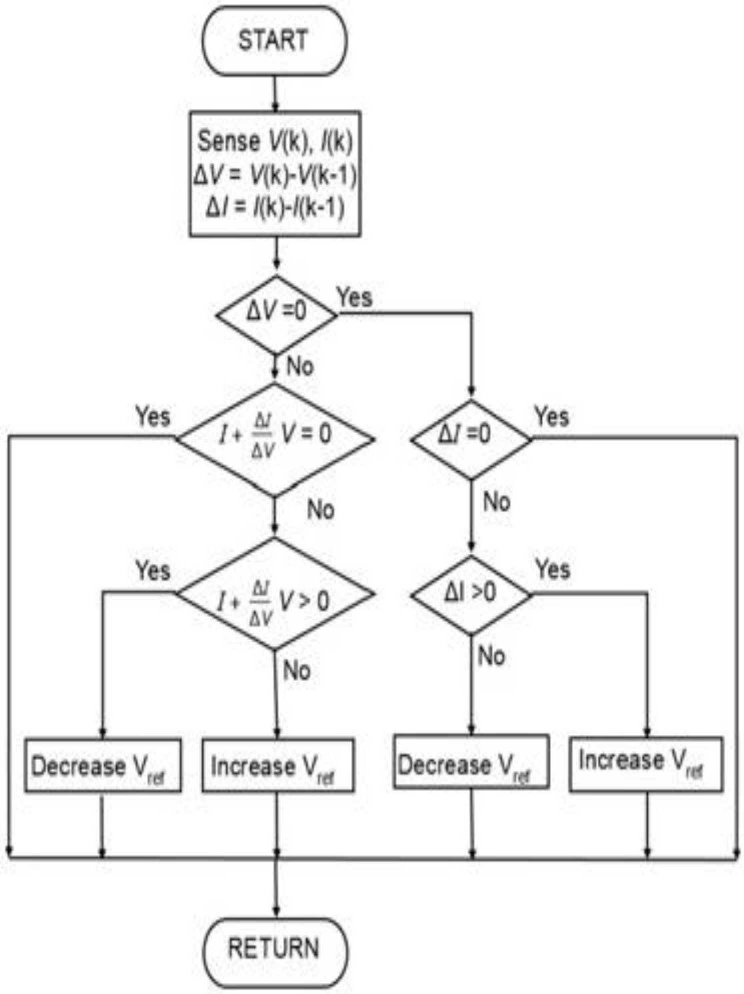


Figure 5.8: Flowchart of the IC algorithm

The left-hand side is the instantaneous conductance of the solar panel. When this instantaneous conductance equals the conductance of the solar then MPP is reached. Here we are sensing both the voltage and current simultaneously. Hence the error due to change in irradiance is eliminated. However the complexity and the cost of implementation increase. As we go down the list of algorithms the complexity and the cost of implementation goes on increasing which may be suitable for a highly complicated system. This is the reason that Perturbs and Observe and Incremental Conductance method is the most widely used algorithms. Owing to its simplicity of implementation we have chosen the Perturb & Observe algorithm for our study among the two.

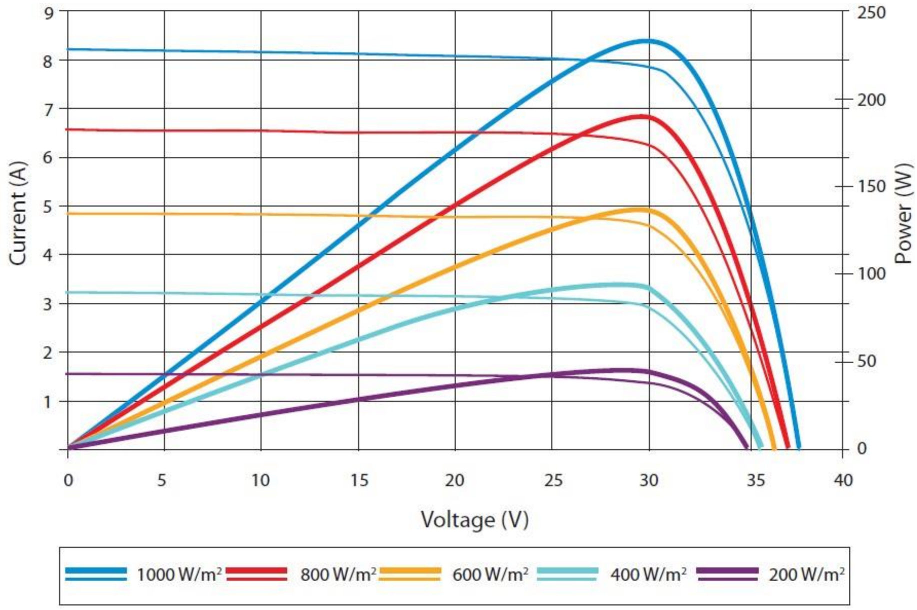


Figure 5.9: PV & IV curve depending on the irradiation

MPPT Technique	Convergence speed	Implementation complexity	Periodic tuning	Sensed parameters
Perturb & observe	Varies	Low	No	Voltage
Incremental Conductance	Varies	Medium	No	Voltage, Current
Fractional V_{oc}	Medium	Low	Yes	Voltage
Fractional I_{sc}	Medium	Medium	Yes	Current
Fuzzy logic control	Fast	High	Yes	Varies
Neural network	Fast	High	Yes	Varies

Table 5.1: Characteristics of different MPPT algorithms

CHAPTER 6

SYSTEM DESCRIPTION AND RESULT

6.1 Solar energy system

6.1.1 Modelling of PV array

The building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts light energy into electricity: it has an equivalent circuit as shown below in Figure 6.1.

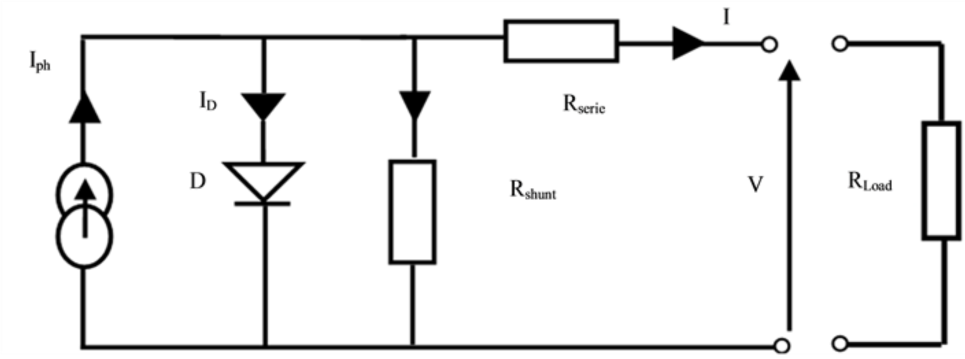


Figure 6.1: Equivalent circuit of a PV cell

The current source I_{ph} represents the cell photocurrent; R_j is used to represent the non-linear impedance of the p-n junction; R_{sh} and Rs are used to represent the intrinsic series and shunt resistance of the cell respectively. Usually, the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis. PV cells are grouped into larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators. The PV mathematical model used to simplify our PV array is represented by the equation:

$$I = n_p I_{ph} - n_p I_{rs}[\exp\{(q/KTA)*V/n_s\}-1] \qquad \text{……… (6.1)}$$

where I is the PV array output current; V is the PV array output voltage; ns is the number of cells in series and np is the number of cells in parallel; q is the charge of an electron; k is the Boltzmann's constant; A is the p-n junction ideality factor; T is the cell temperature (K); I_{rs} is the cell reverse saturation current. The factor A in equation (6.1) determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1-5 but for our case A=2.46.

The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$\mathbf{I_{rs} = I_{rr}[T/T_r]^3 \exp((qE_G/KA[1/T_r - 1/T])} \qquad \text{........ (6.2)}$$

Where Tr is the cell reference temperature, I_{rr} is the cell reverse saturation temperature at T_r and E_G is the band gap of the semiconductor used in the cell.

The temperature dependence of the energy gap of the semiconductor is given by:

$$\mathbf{E_G = E_G(0) - \alpha T^2/T+\beta} \qquad \text{.......... (6.3)}$$

The photocurrent Iph depends on the solar radiation and cell temperature as follows:

$$\mathbf{I_{ph} = [I_{scr} + K_i(T - T_r)]*S/100} \qquad \text{.......... (6.4)}$$

Where I_{scr} is the cells short-circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm2. The PV power can be calculated using equation (6.1) as follows:

$$\mathbf{P = IV = n_{ph} I_{ph} V [\{(q/KTA)*V/n_s\} -1]} \qquad \text{......... (6.5)}$$

6.1.2 PV array characteristics curves

The current to voltage characteristic of a solar array is non-linear, which makes it difficult to determine the MPP. The *Sunpower SPR-445NX-WHT-D* array is applied to simulate the PV system using a normal model of a solar cell for a photovoltaic module.

Specification of PV array –

Max. Power (W)	444.86
Cells per module (Ncell)	128
Open circuit voltage V_{oc} (V)	90.5
Short-circuit current I_{sc} (A)	6.21
Voltage at MPP	76.7
Current at MPP	5.8

Table 6.1: Specification of PV array.

- The Figure below gives the characteristic I-V and P-V curve for various solar irradiance (1000 750 500 250) W/m^2 but a fixed temperature (25^{o}C).

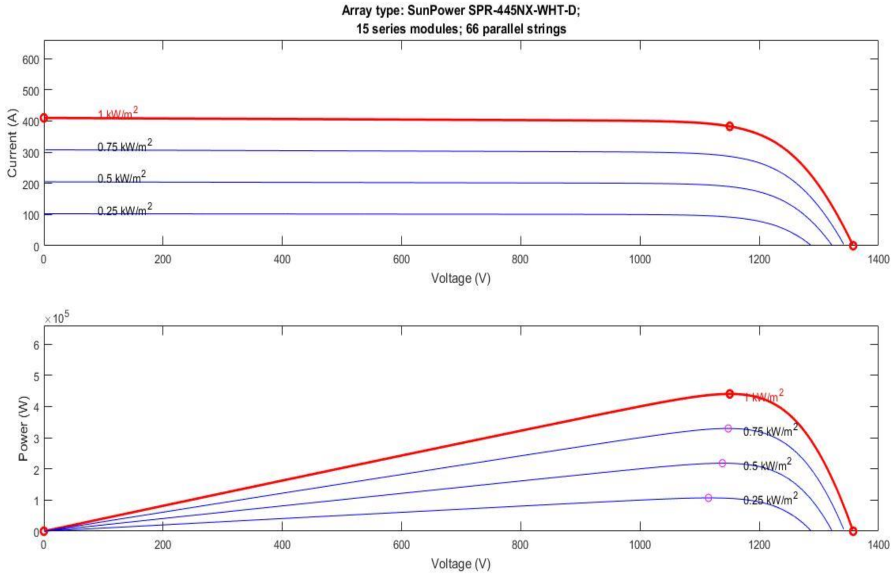


Figure 6.2: I-V & P-V characteristics of PV array at different irradiance.

- The Figure below gives the characteristic I-V and P-V curve for various solar temperature (25 35 45 50) ^{0}C but a fixed irradiance (1000) W/m^2.

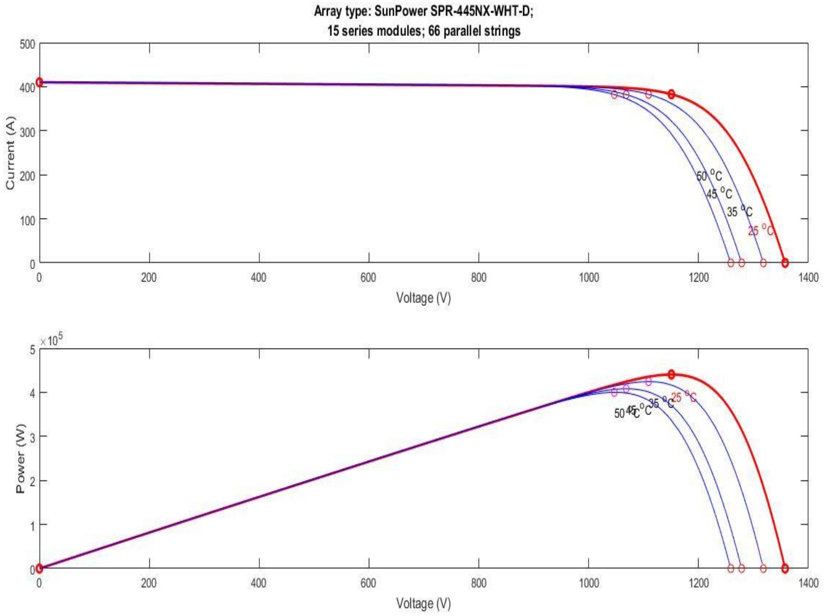


Figure 6.3: I-V & P-V characteristics of PV array at a different temperature.

The characteristic I-V curve tells that there are two regions in the curve: one is the current source region and another is the voltage source region. In the voltage source region (on the right side of the curve), the internal impedance is low and in the current source region (on the left side of the curve), the impedance is high. Irradiance temperature plays an important role in predicting the I-V characteristic, and effects of both factors have to be considered while designing the PV system. Whereas the irradiance affects the output, temperature mainly affects the terminal voltage.

From the I-V, we observe that the short circuit current increases with increase in irradiance at a fixed temperature. Moreover, from the I-V and P-V curves at a fixed irradiance, it is observed that the open circuit voltage decreases with increase in temperature.

6.1.3 Complete simulation model of PV system

The PV array has been interfaced with the boost converter, MPPT controller, and DC-AC inverter as shown in figure (6.4).

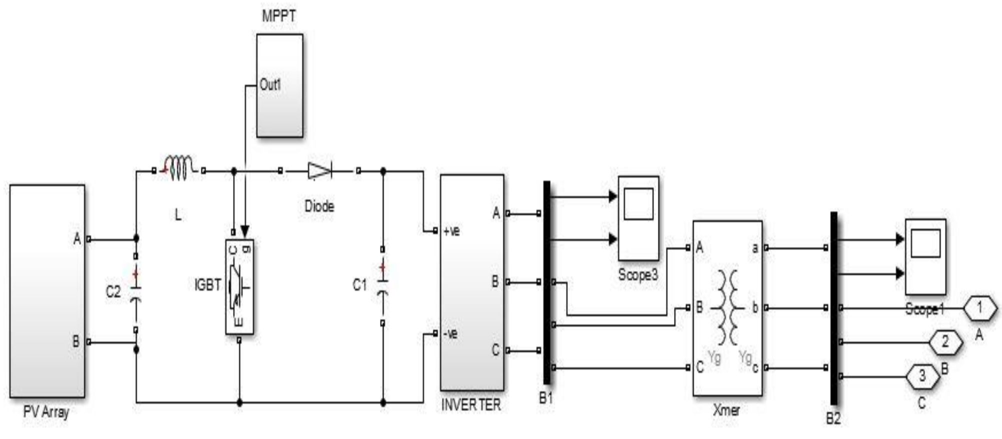


Figure 6.4: A simulation model of PV system.

The PV array has been designed taken into consideration its dependence upon the irradiance, temperature, number of PV cells.

6.1.3.1 Output of the PV system

- Input voltage of the boost converter

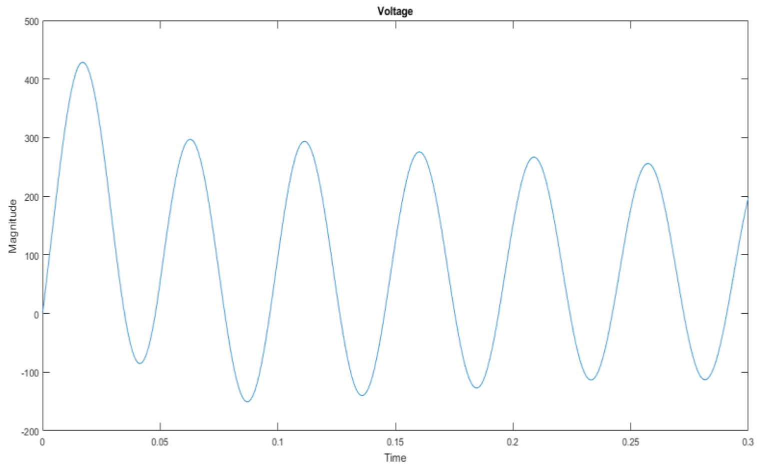


Figure 6.5: Input voltage of boost converter.

- Output voltage of boost converter:

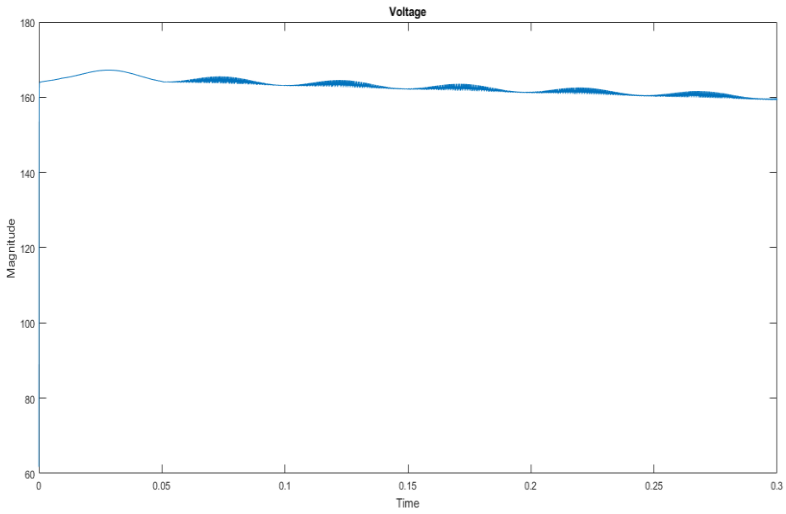


Figure 6.6: Output voltage of boost converter.

- Output voltage and current of inverter:

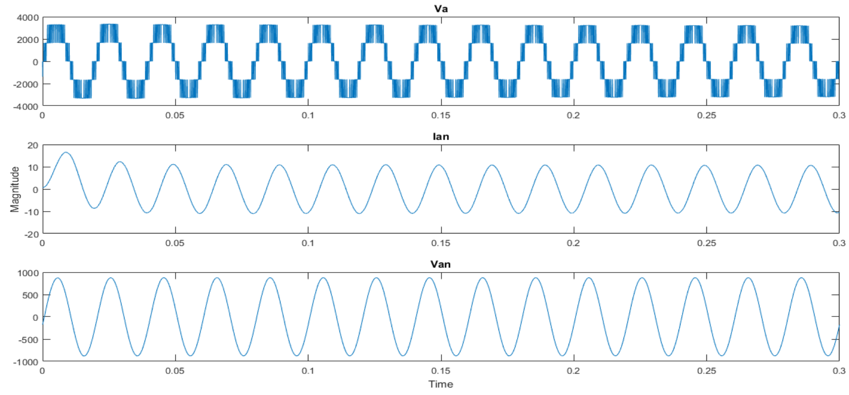


Figure 6.7: Output voltage and current of inverter.

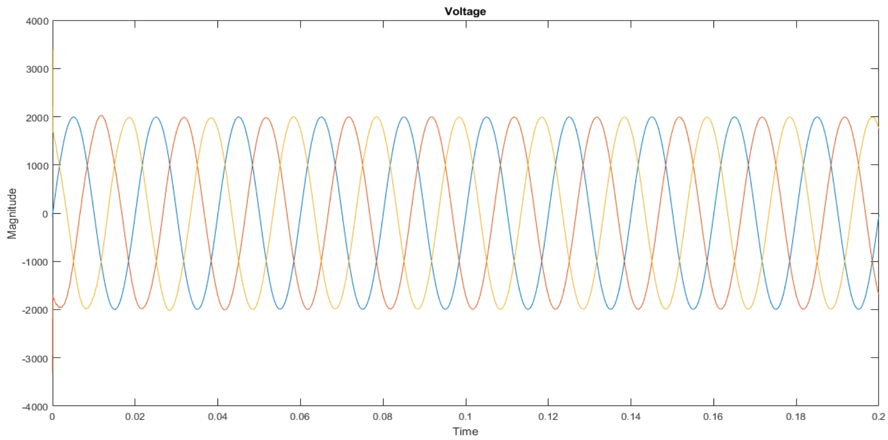


Figure 6.8: Output voltage of PV system.

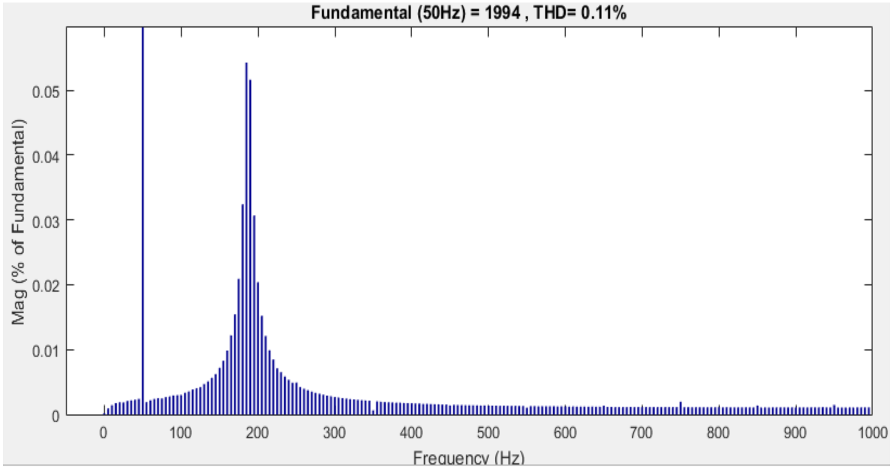


Figure 6.9: THD of PV system.

6.2 Wind energy system

6.2.1 Modelling of wind turbine

A wind turbine converts the kinetic energy of air i.e. wind power into mechanical power i.e. rotating motion of the turbine that can be used directly to run the machine or generator. Power captured by wind turbine blade is a concomitant of the blade shape, the pitch angle, the speed of rotation, the radius of the rotor [21]. The equation for the power generated is shown below.

$$\mathbf{P_m = 0.5\ \pi\rho\ C_p\ (\lambda, \beta)\ R^2\ V^3} \qquad \text{……… (6.6)}$$

Where,

P_m – Power captured by wind turbine, ρ – Air density

β – Pitch angle (in degree), R – Blade radius (in meter)

V – Wind speed (in m/s)

The term λ is the tip-speed ratio, given by the equation

$$\mathbf{\lambda = \Omega R/V} \qquad \text{………… (6.7)}$$

Where,

Ω - Rotor speed of rotation (in rad/sec).

Specification of wind turbine

Nominal mech. Output power (W)	1.5e6
Base power of elec. Generator (VA)	1.5e6/0.9
Base wind speed (m/s)	14
Max. power at a base wind speed	0.8
Base rotational speed	1
Pitch angle (β >= 0) (deg.)	0

Table 6.2: Specification of WT.

- Characteristics curve of turbine speed and power, when pitch angle is zero.

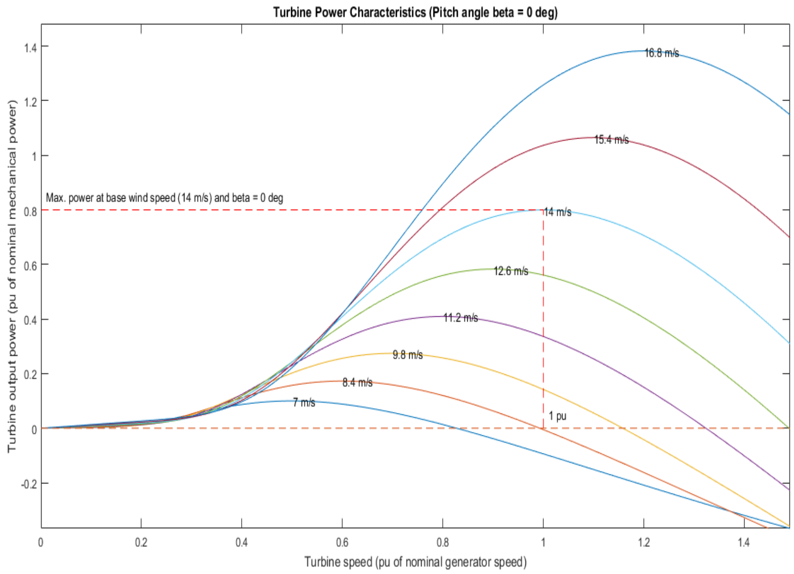


Figure 6.10: Characteristics of power & speed of the turbine.

6.2.2 Complete simulation model of wind turbine system

The wind system has been interfaced with the rectifier, boost converter, MPPT controller and DC-AC inverter as shown in figure (6.8).

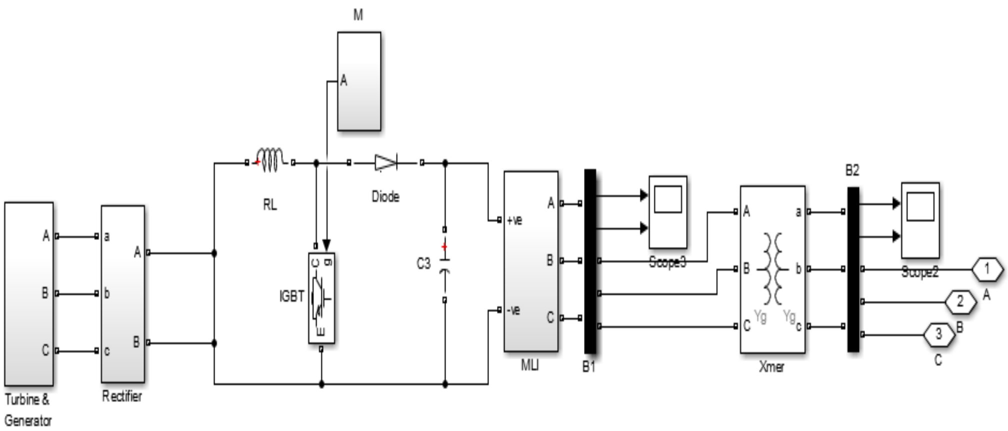


Figure 6.11: A simulation model of Wind turbine.

6.2.2.1 Output of the wind system

- Input voltage of boost converter:

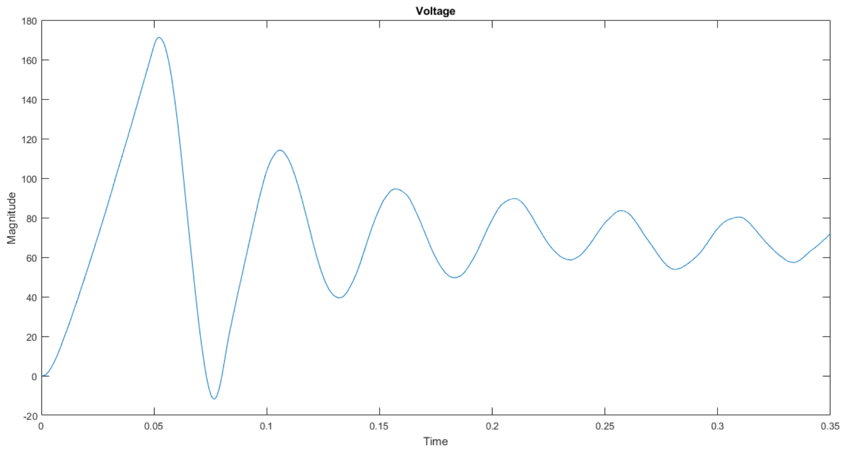


Figure 6.12: Input voltage of boost converter.

- Output voltage of boost converter:

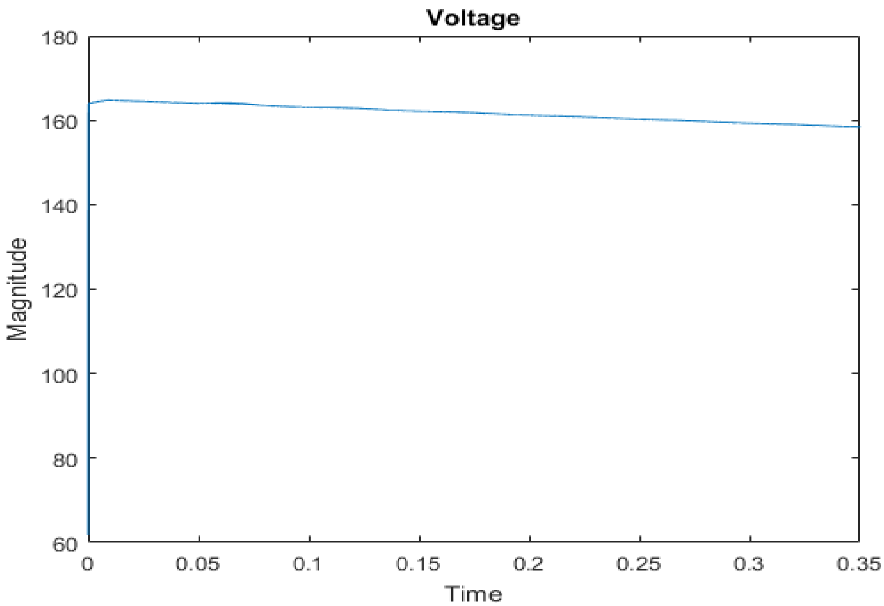


Figure 6.13: Output voltage of boost converter.

- Output voltage and current of inverter.

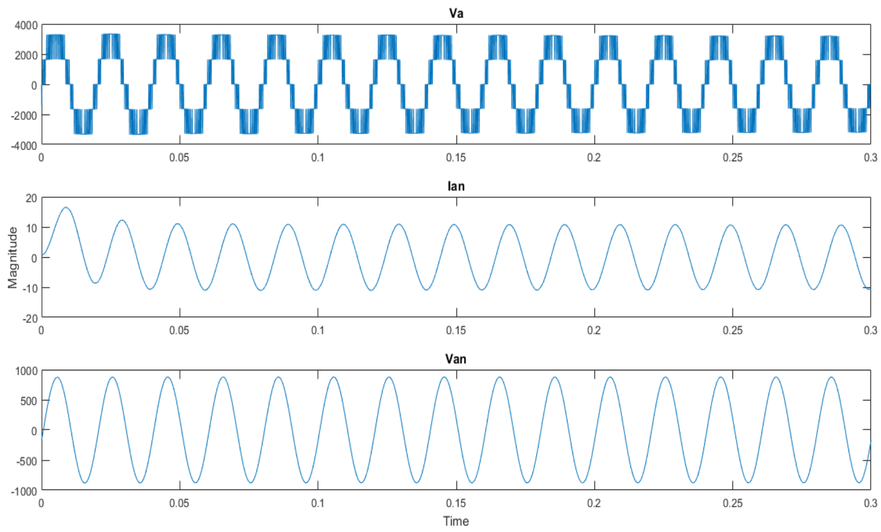


Figure 6.14: Output voltage and current of inverter.

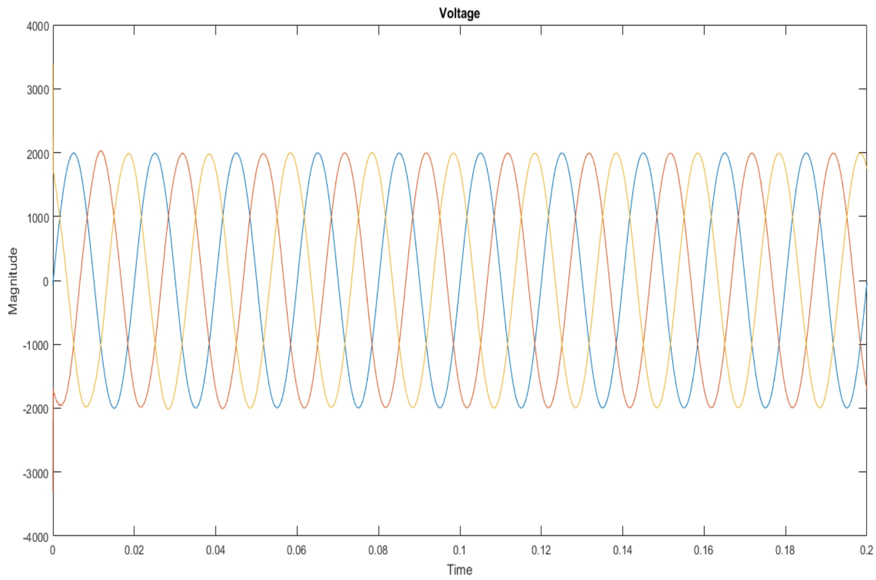


Figure 6.15: Output voltage of wind system.

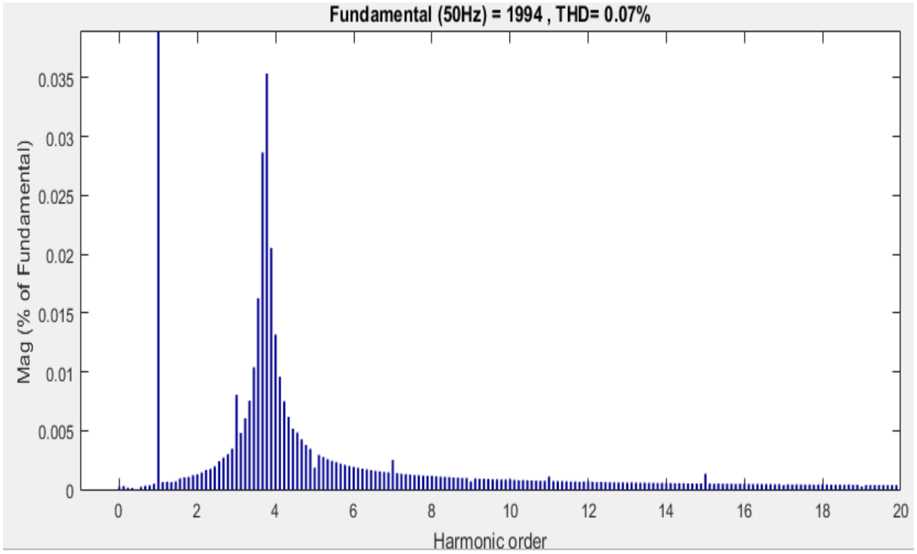


Figure 6.16: THD of the wind system.

6.3 Simulation model of microgrid connected hybrid system

The PV-wind hybrid system has been interfaced with the rectifier, boost converter, MPPT controller and DC-AC inverter connected to the microgrid as shown in figure (6.11).

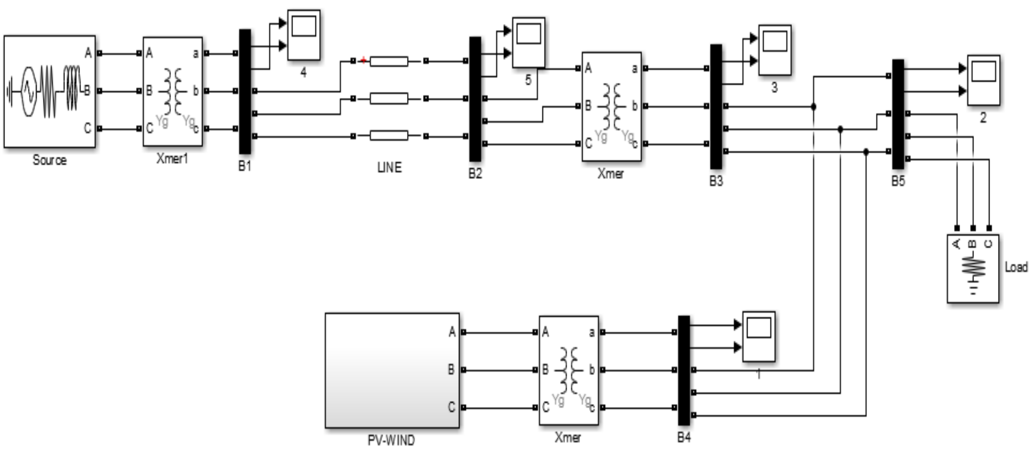


Figure 6.17: A simulation model of PV-wind hybrid system with the micro grid.

6.3.1 Output of the PV-wind hybrid system

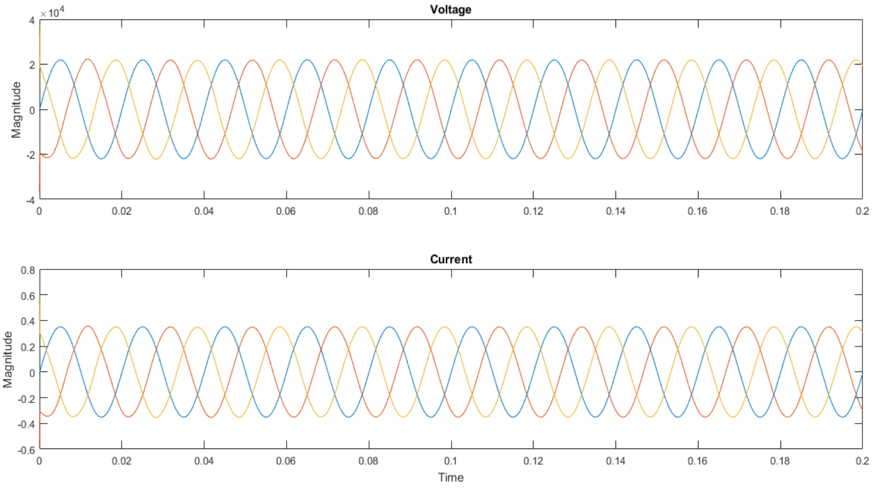


Figure 6.18: Output voltage & current of PV-wind hybrid system at load.

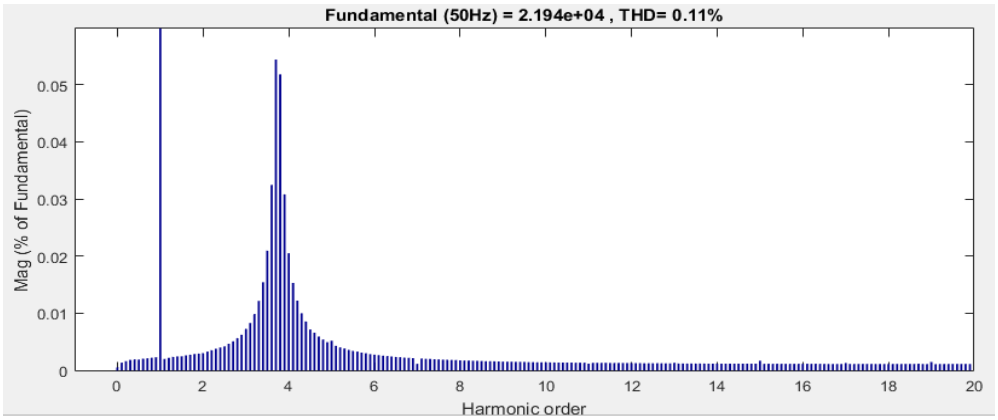


Figure 6.19: THD of the voltage of hybrid system at load.

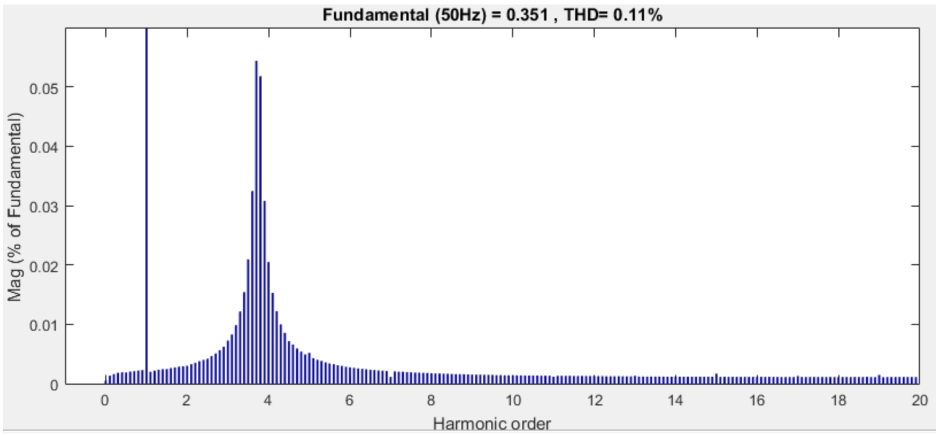
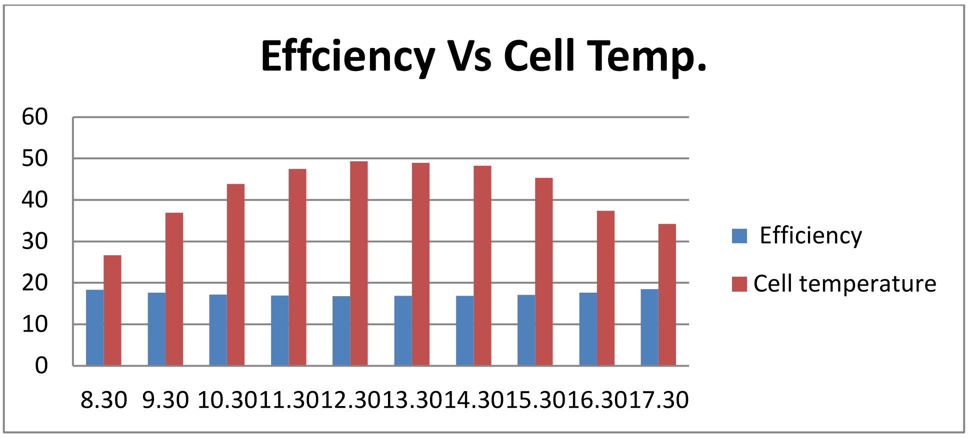


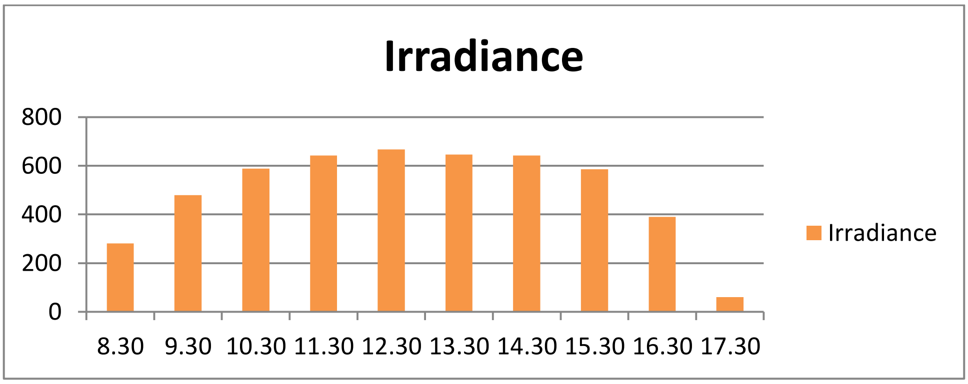
Figure 6.20: THD of the current of the hybrid system at load.

6.4 Variations in metrological quantities

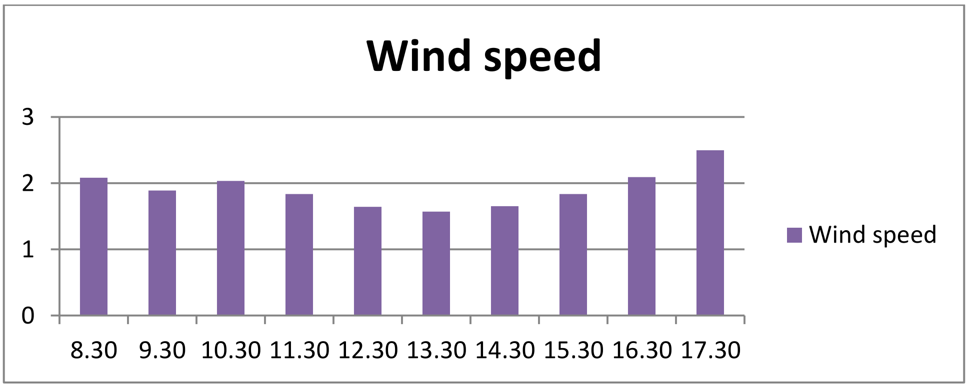
- **January**



(a)



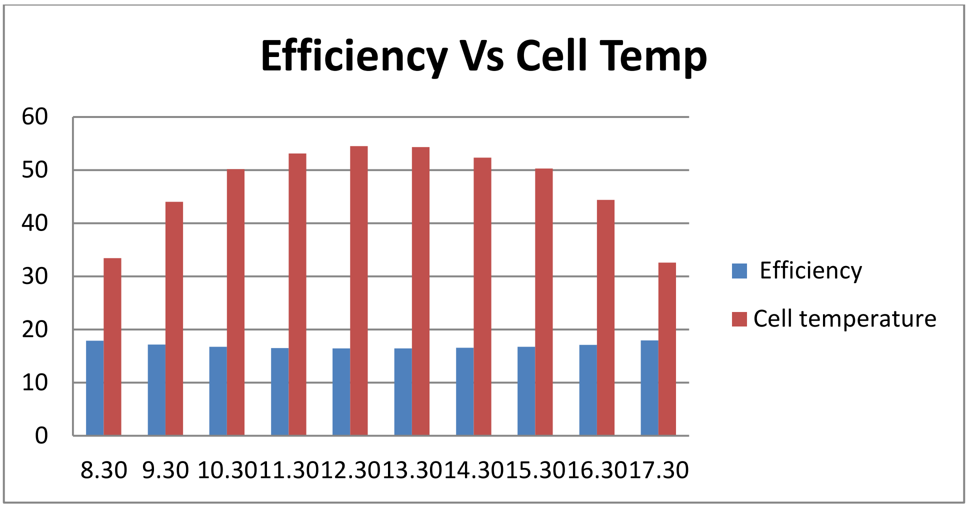
(b)



(c)

Figure 6.21: Graph of efficiency vs cell temp., irradiation and wind speed in January.

- **February**



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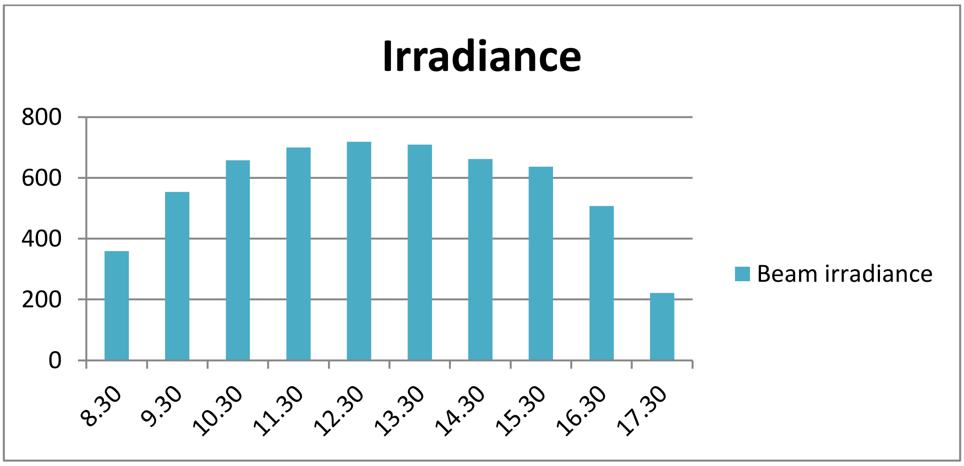

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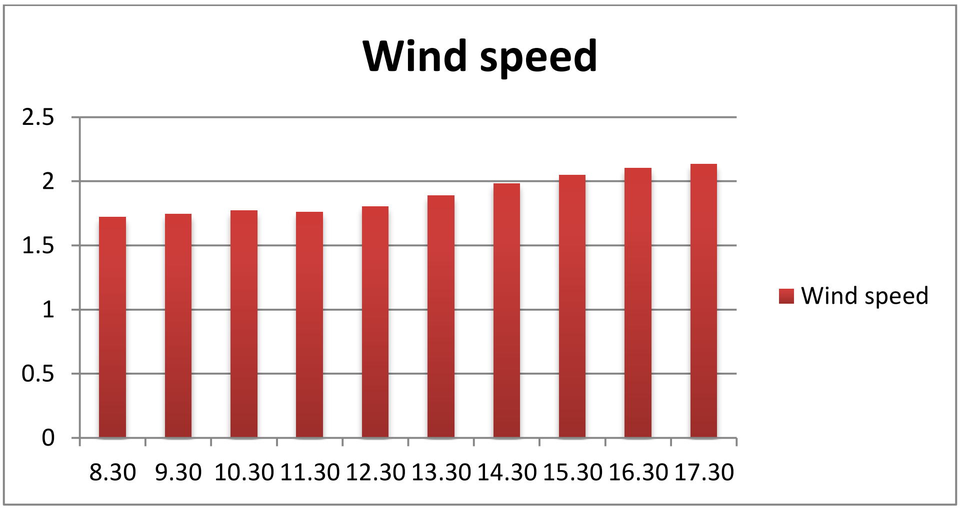
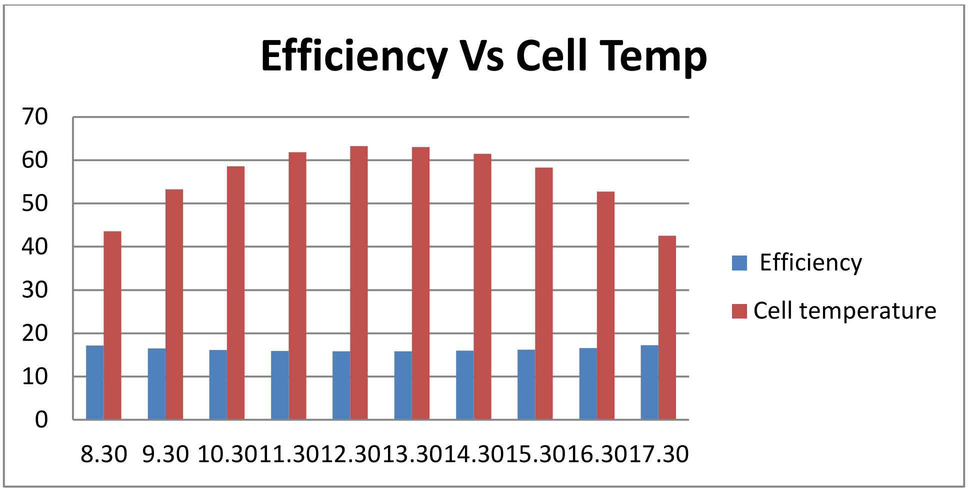


(c)

Figure 6.22: Graph of efficiency vs cell temp., irradiation and wind speed in February.

- **March**



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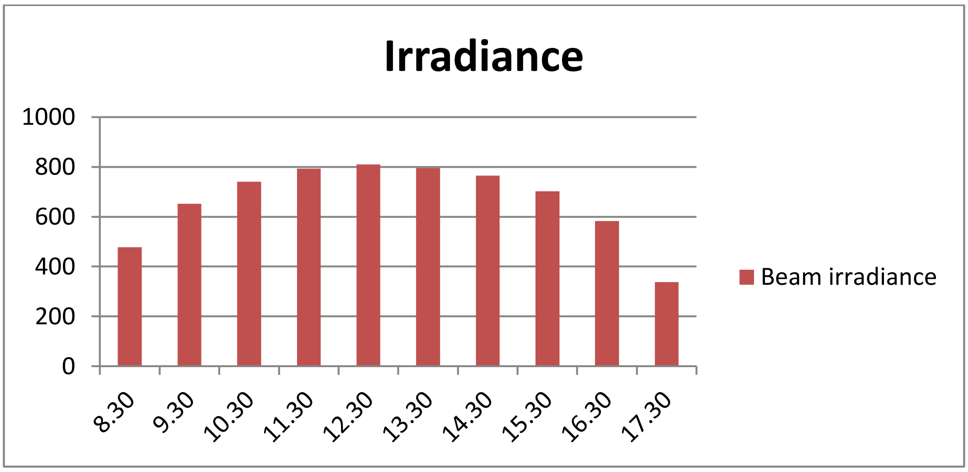

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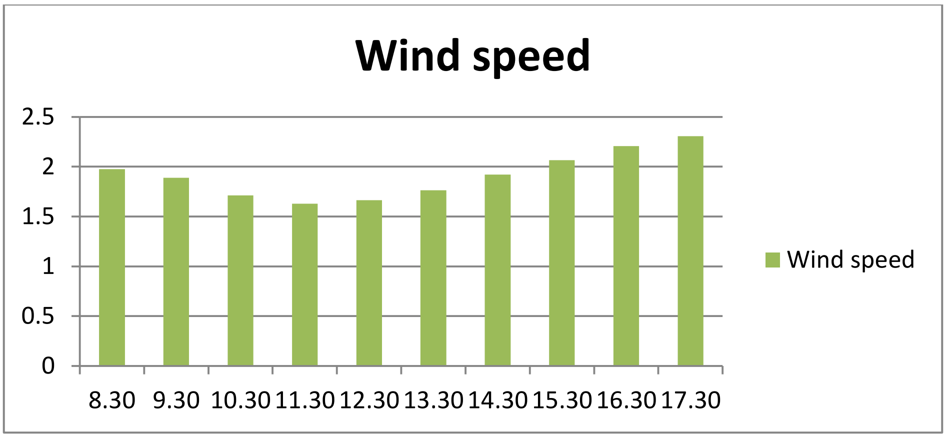
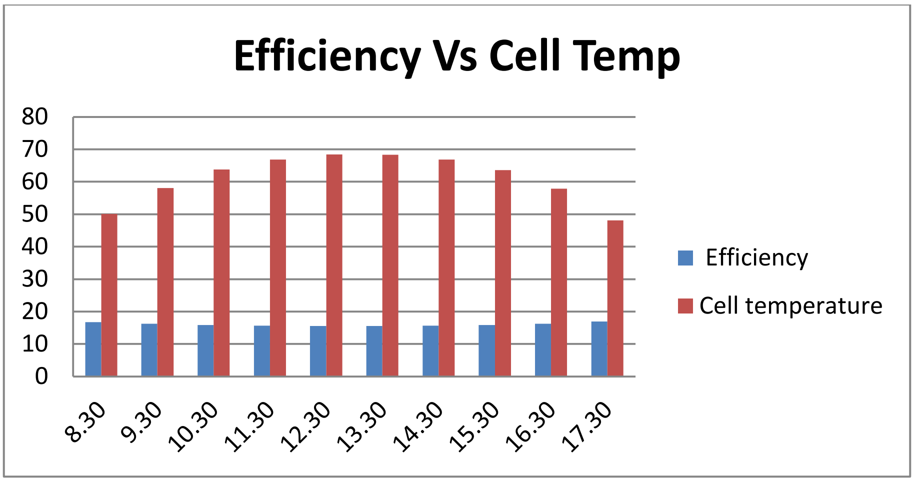


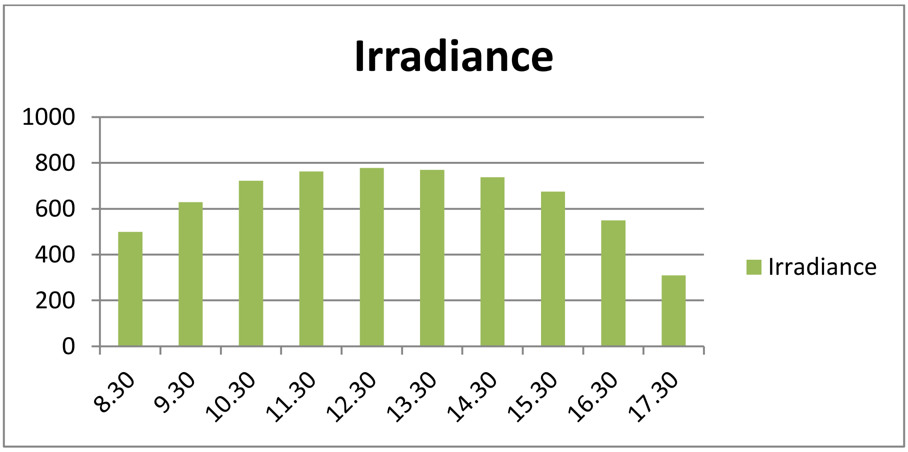
(c)

Figure 6.23: Graph of efficiency vs cell temp., irradiation and wind speed in march.

- **April**



(a)



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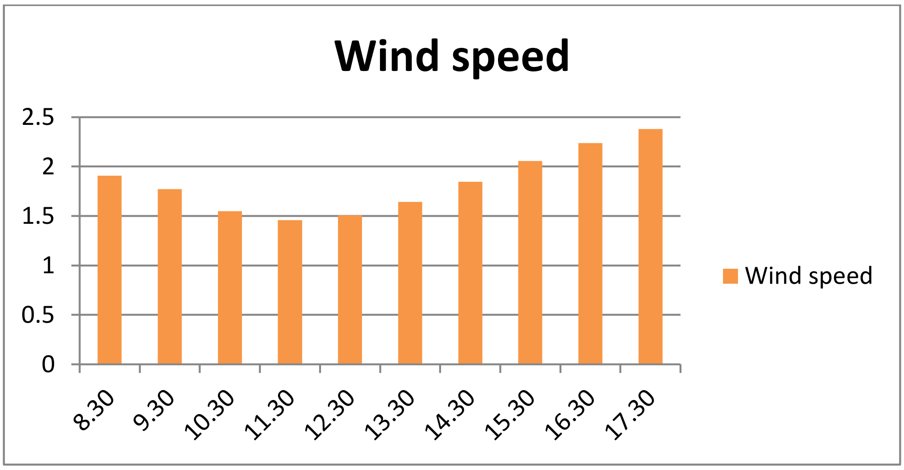
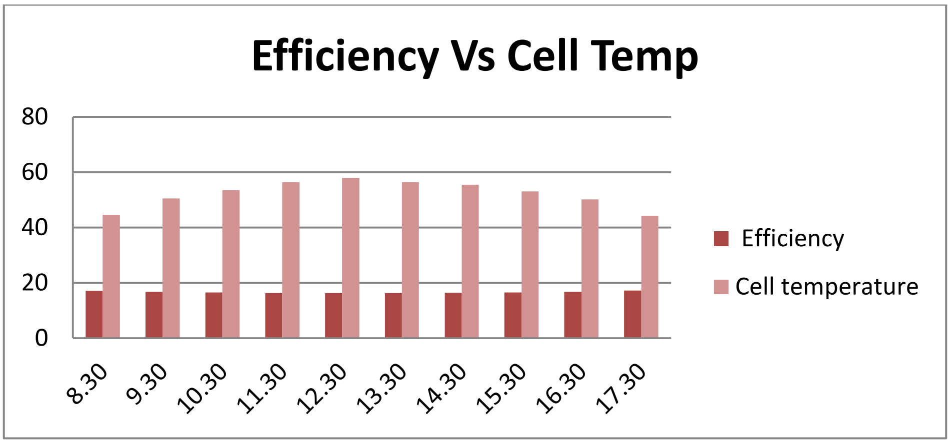


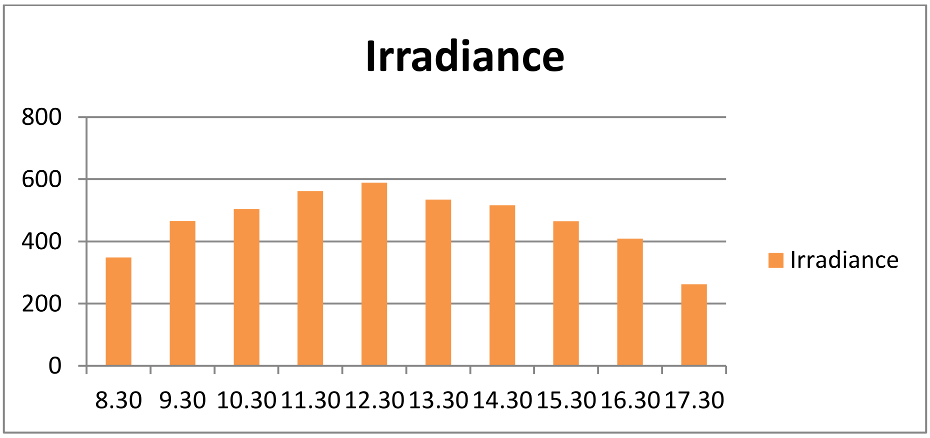
(c)

Figure 6.24: Graph of efficiency vs cell temp., irradiation and wind speed in april.

- **May**



(a)



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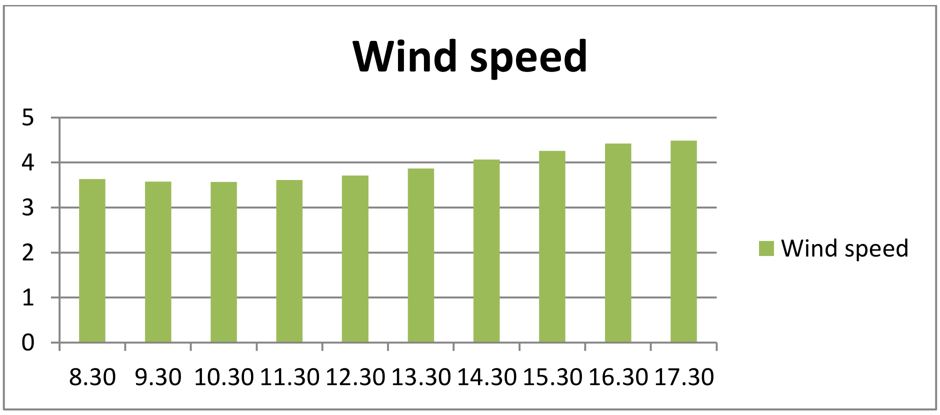
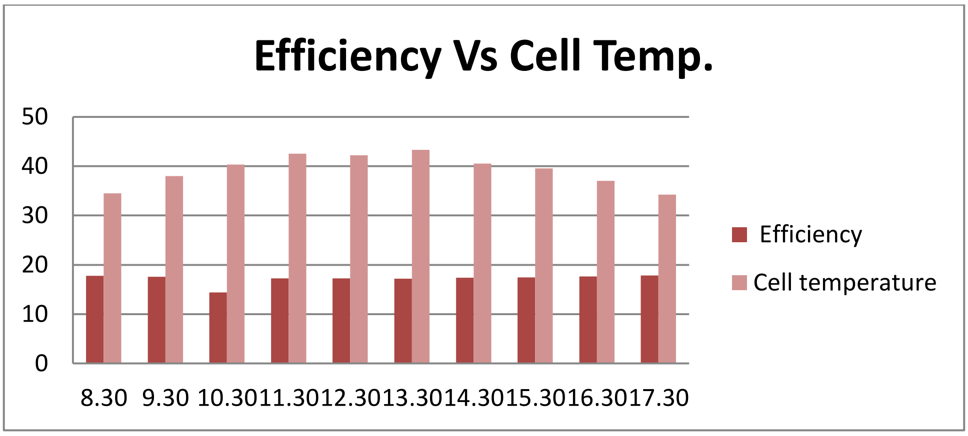


(c)

Figure 6.25: Graph of efficiency vs cell temp., irradiation and wind speed in may.

- **June**



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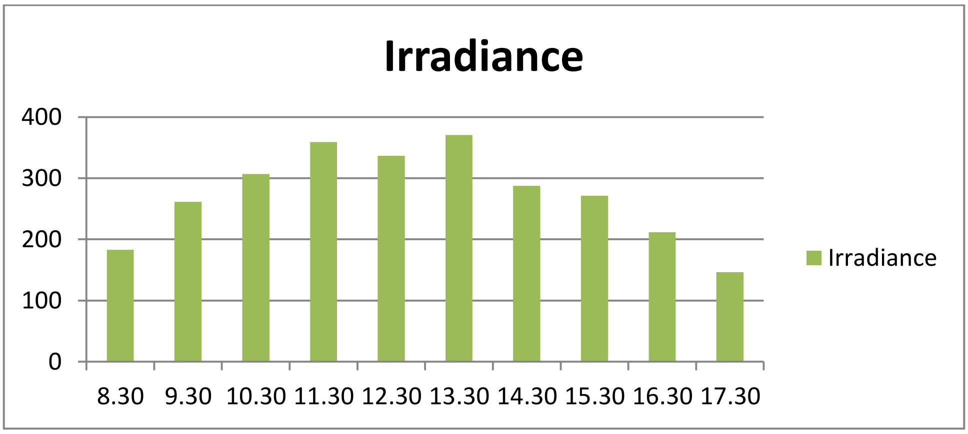

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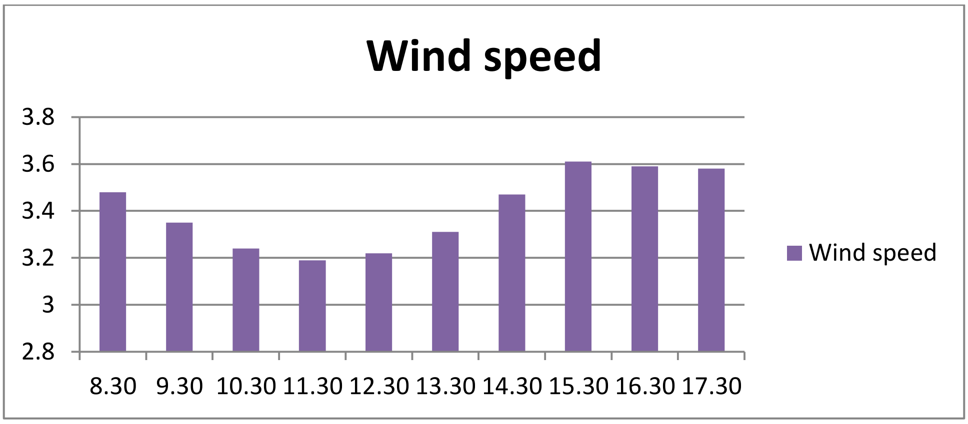

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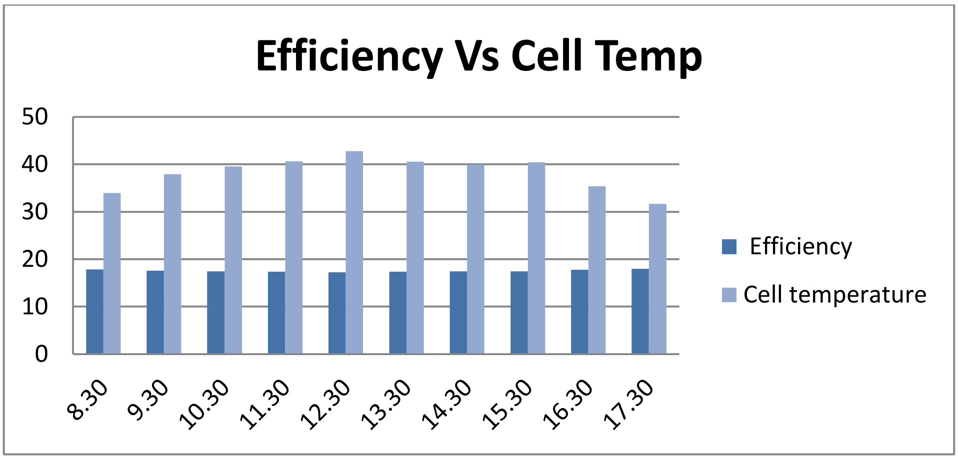
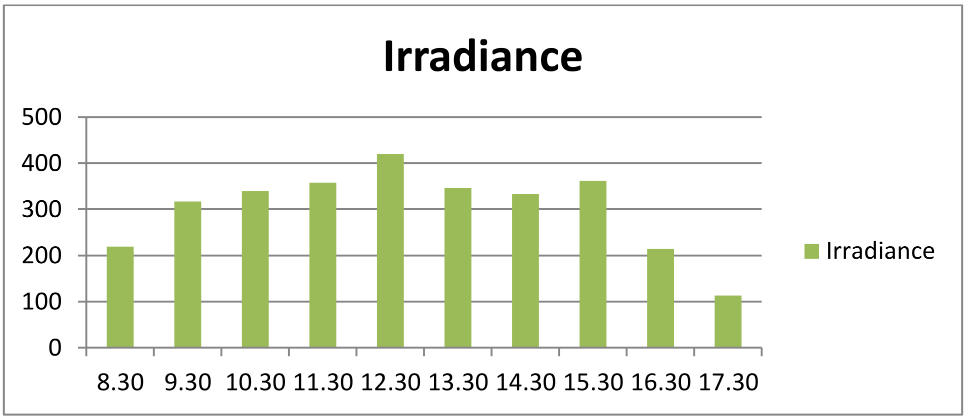
Figure 6.26: Graph of efficiency vs cell temp., irradiation and wind speed in june.

- **July**



(a)



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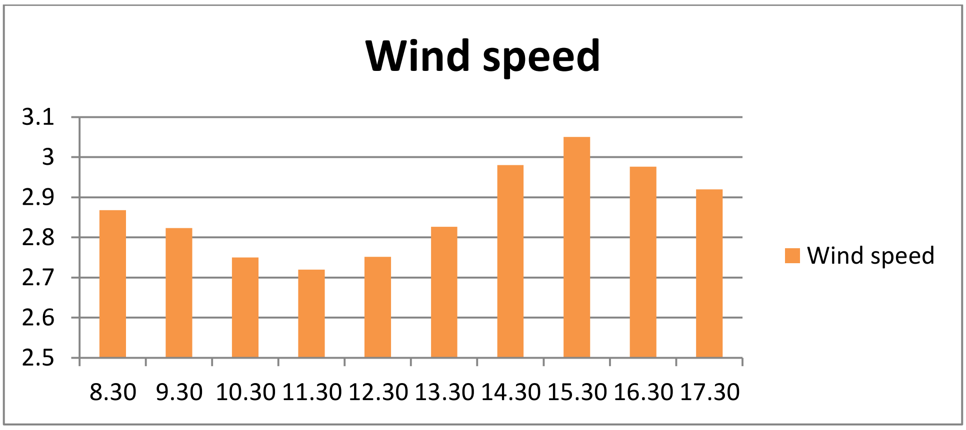
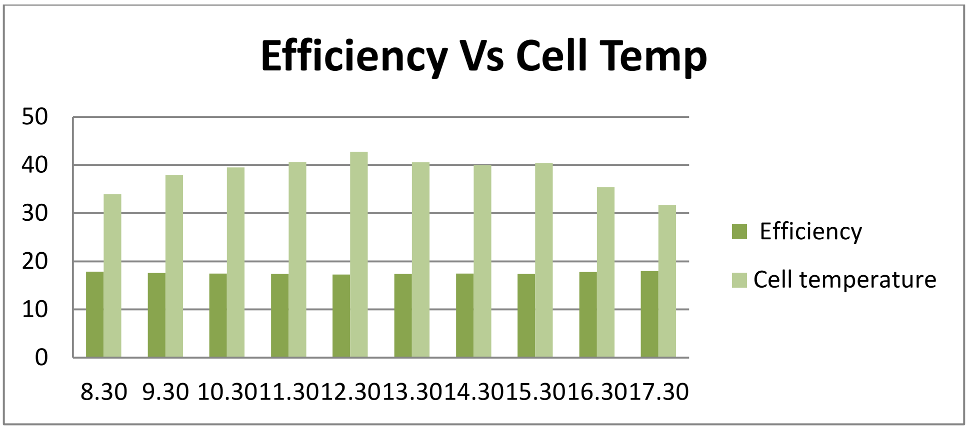


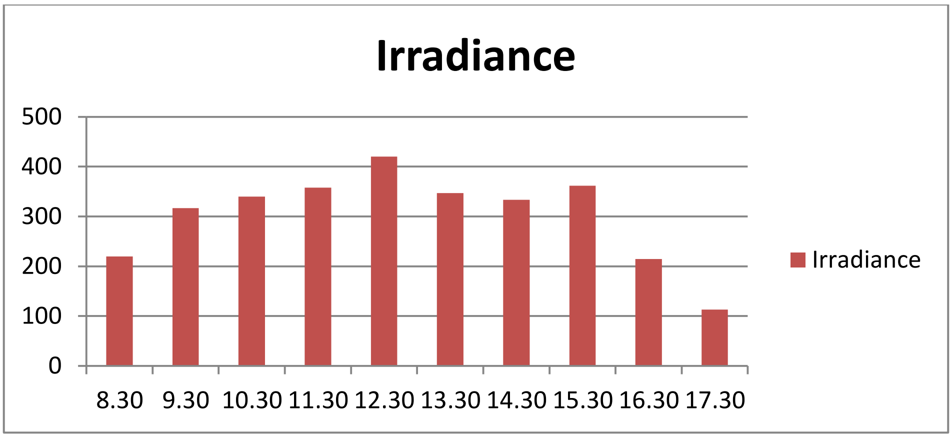
(C)

Figure 6.27: Graph of efficiency vs cell temp., irradiation and wind speed in july.

- **August**



(a)



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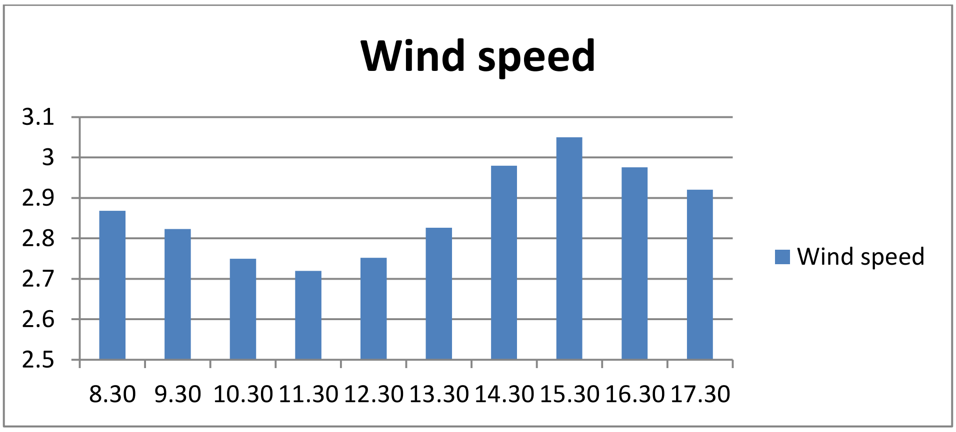

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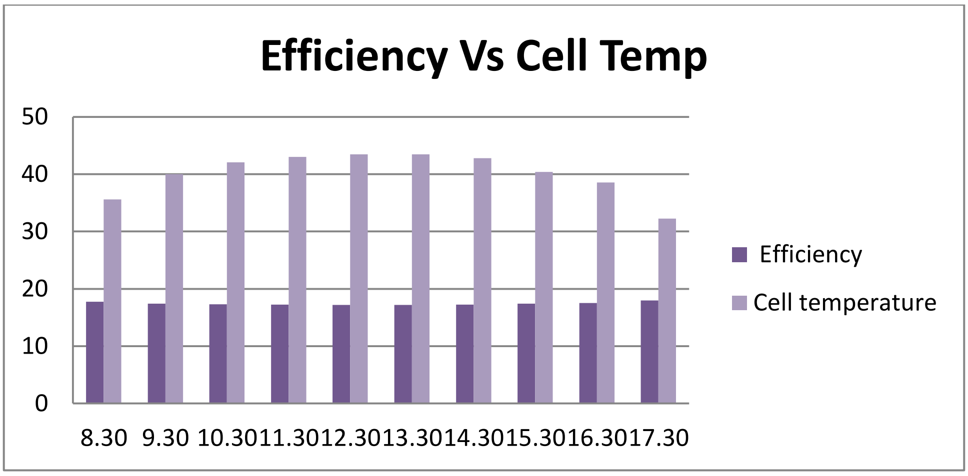
Figure 6.28: Graph of efficiency vs cell temp., irradiation and wind speed in august.

- **September**



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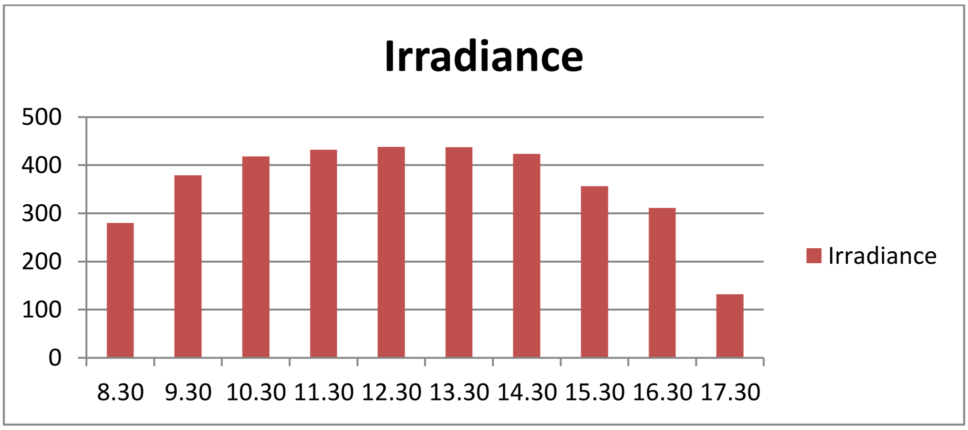

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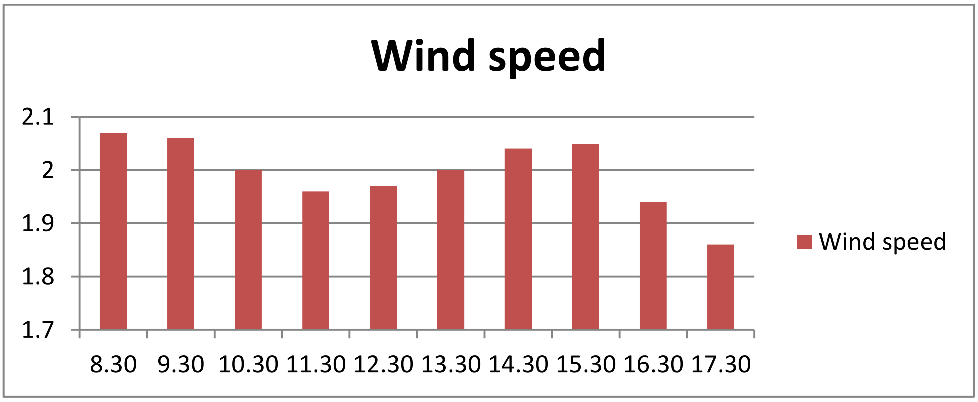
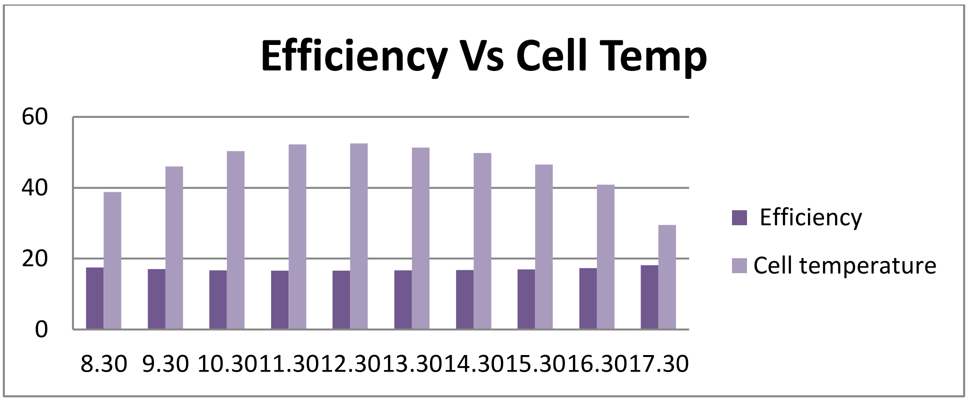


(c)

Figure 6.29: Graph of efficiency vs cell temp., irradiation and wind speed in September.

- **October**



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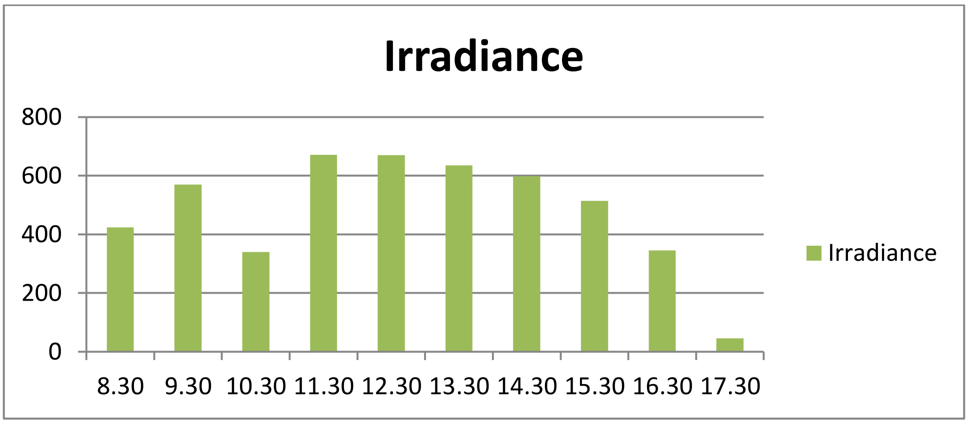
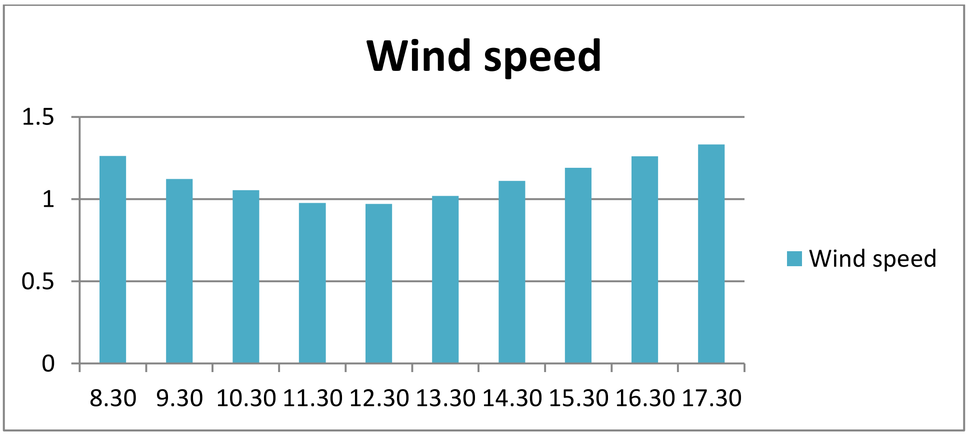


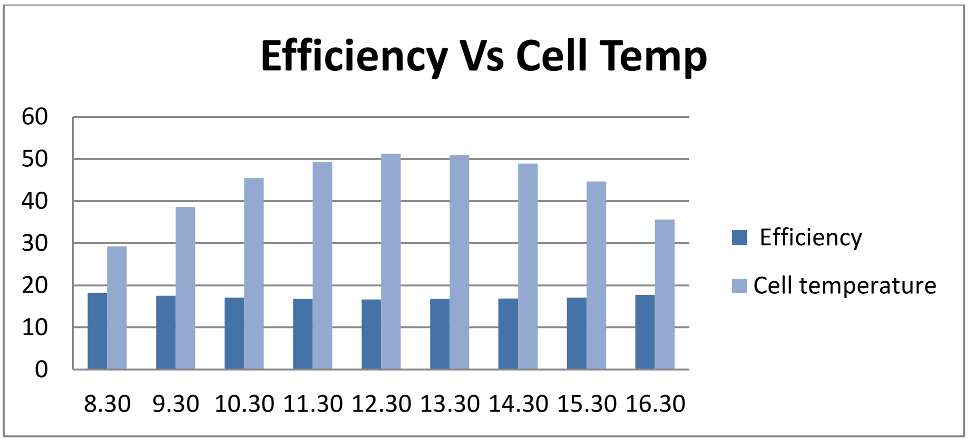
(b)



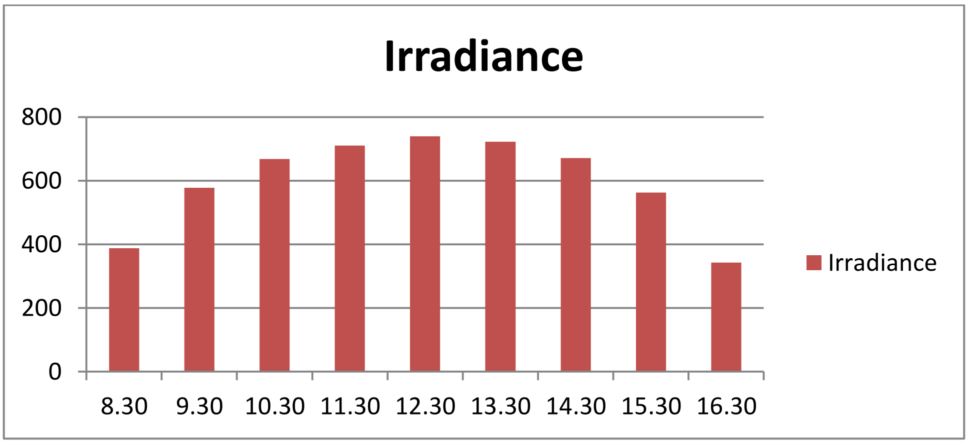
(c)

Figure 6.30: Graph of efficiency vs cell temp., irradiation and wind speed in October.

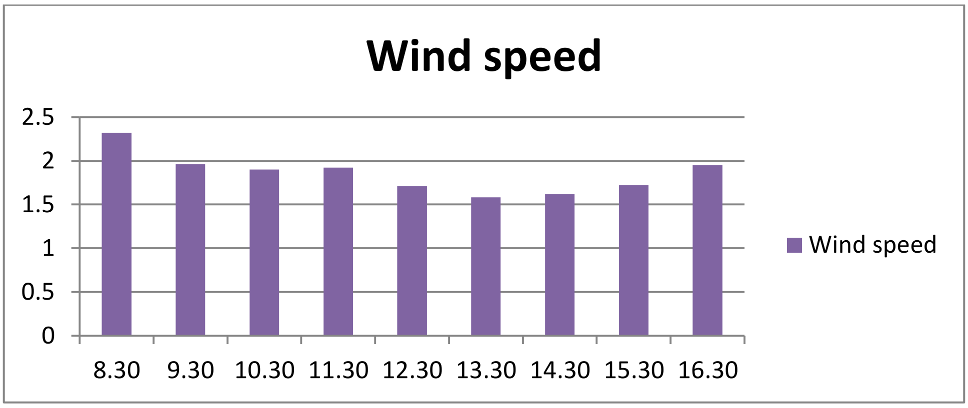
- **November**



(a)



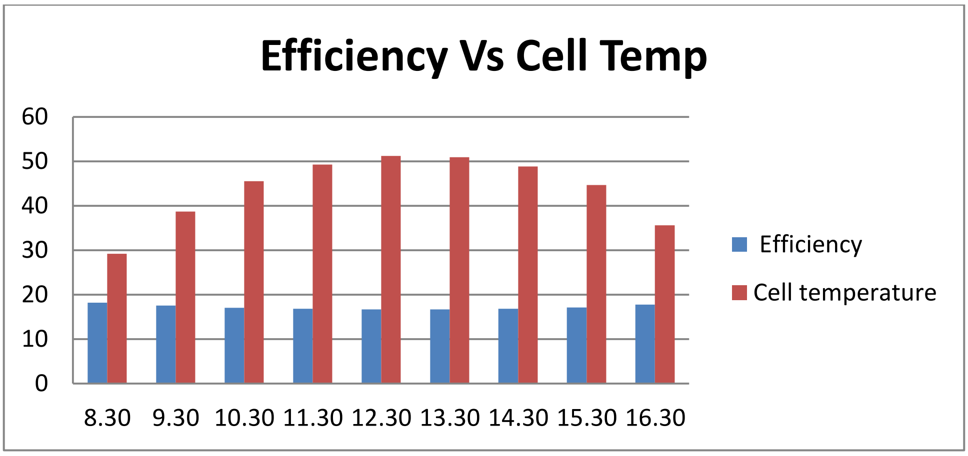
(b)



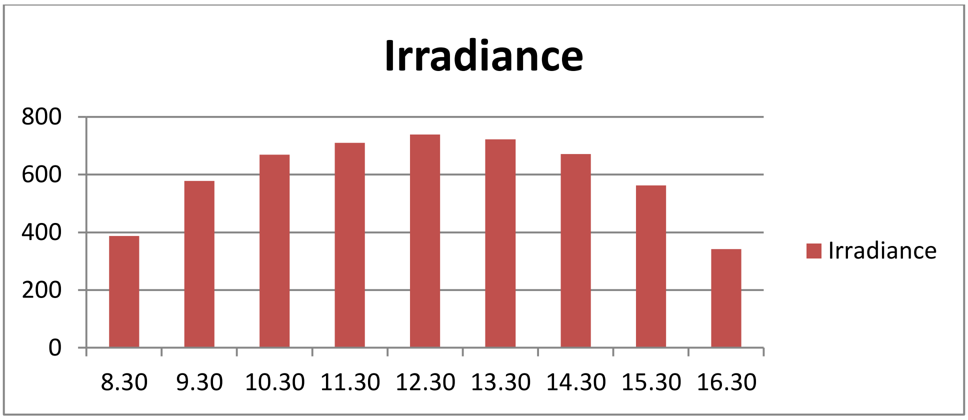
(c)

Figure 6.31: Graph of efficiency vs cell temp., irradiation and wind speed in November.

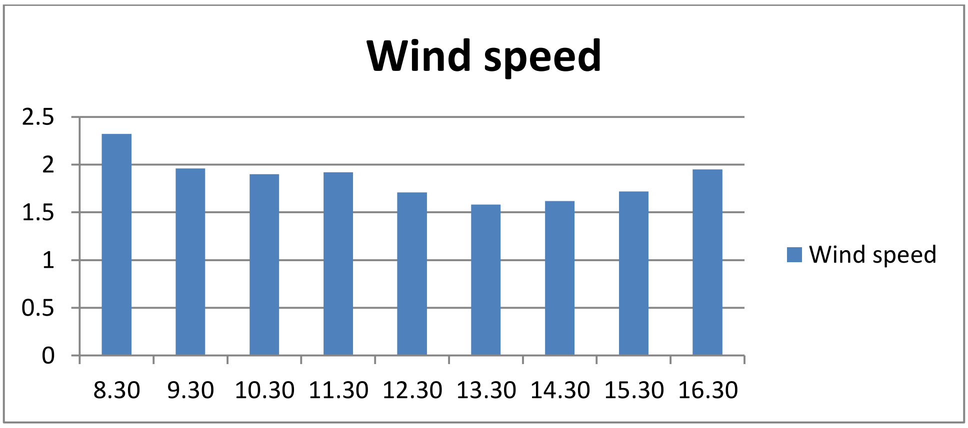
- **December**



(a)



(b)



(c)

Figure 6.32: Graph of efficiency vs cell temp., irradiation and wind speed in December.

CHAPTER-7
CONCLUSION AND FUTURE SCOPE

7.1 Solar System

The open circuit P-V, P-I, I-V curves explain in detail their dependence on the irradiation levels and temperatures. The various values of the voltage and current obtained have been plotted in the open circuit I-V curves of the PV array at insolation levels of 1000 W/ m^2. The voltage and current values lie on the curve showing that the coupling of the PV array with the boost converter is proper. However, the performance of the photovoltaic device depends on the spectral distribution of the solar radiation.

Topolgy	**THD in voltage**	**THD in current**
5-levels	29.35	28.21
Improved 5-levels	0.11	5.99

Table 7.1: THD analysis in PV system.

7.2 Wind Farm

In this thesis work, Electric power has been generated from the wind by wind turbo-generator set. The produced voltage is given to the rectifier where rectifier converts it into smooth DC voltage by using a bridge rectifier. This dissertation work proposed a reduction of THD at load side.

Topolgy	**THD in voltage**	**THD in current**
5-levels	29.35	28.21
Improved 5-levels	0.11	5.98

Table 7.2: THD analysis in wind system.

7.3 PV-wind hybrid system

- PV cell, module, and array are simulated and effect of environmental conditions on their characteristics is studied
- Wind energy system has been studied and simulated.

- A maximum power point of operation is tracked for both the systems using incremental conductance technique.

7.4 Future scope

The hybrid renewable energy generation is our future energy. Research on hybrid energy combinational issues can become continuation of this work. Based on several studies and this study suggest some of the scopes for further study. A detailed simulation study on hybrid generation is required. In this study few problems are addressed still many to be addressed which are listed as follows:

- To carry out simulation study on hybrid energy systems for power quality analysis.
- MPP can be tracked using different algorithms.
- Smart grid simulation approach for hybrid energy management.
- Based on the availability of renewable energy the hybrid wind/solar energy combination can be replaced by wind/solar/biomass, wind/solar/fuel cells etc to meet the global demand.
- By using FACTS devices with the system transient response of the PV-wind suystem can be improved.
- Harmonics produced with the operation of variable speed wind turbines can be analysed and that can be reduced by designing active filters or passive filters and voltage and current waveforms can be smoothened well.

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APPENDIX

Table no. 1: January metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	281.484	101.581	2.08201	18.34263	26.6433765	46.9
9.30	479.806	159.129	1.88638	17.64822	36.89140725	46.9
10.30	587.806	195.871	2.03203	17.17578	43.86350725	46.9
11.30	641.71	209.839	1.83433	16.92829	47.51594125	46.9
12.30	666.452	222.581	1.64347	16.8036	49.3561795	46.9
13.30	645.806	223.677	1.57148	16.83246	48.93025725	46.9
14.30	642.161	209.677	1.65419	16.87602	48.28734038	46.9
15.30	585.161	177.452	1.83714	17.07716	45.31896538	46.9
16.30	389.645	149.677	2.09093	17.61572	37.37106688	46.9
17.30	59.9677	59.8387	2.49844	18.50649	34.22511889	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	42.07804	2.64595	38.4	38.168284	100.9914	
9.30	40.91937	4.510176	38.4	36.723312	165.6286	
10.30	40.01536	5.525376	38.4	35.740245	197.4783	
11.30	39.53406	6.032074	38.4	35.225252	197.4783	
12.30	39.29298	6.264649	38.4	34.965779	197.4783	
13.30	39.36502	6.070576	38.4	35.025834	197.4783	
14.30	39.444375	6.036313	38.4	35.116485	197.4783	
15.30	39.84603	5.500513	38.4	35.535026	197.4783	
16.30	40.85408	3.662663	38.4	36.65568	197.4783	
17.30	40.54325	0.563696	38.4	38.509258	197.4783	

Table no. 2: February metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	359.25	116.71	1.72091	17.88097	33.45641875	46.9
9.30	553.964	171.43	1.74483	17.16567	44.0127565	46.9
10.30	657.25	194.46	1.77232	16.7479	50.17816875	46.9
11.30	699.75	221.86	1.76163	16.54832	53.12350625	46.9
12.30	718.321	237.96	1.80359	16.45303	54.52970038	46.9
13.30	708.75	217.93	1.88847	16.46535	54.34788125	46.9
14.30	661.5	214.57	1.98231	16.60179	52.3343625	46.9
15.30	636.607	189.29	2.04818	16.74016	50.29233763	46.9
16.30	507.393	153.36	2.10222	17.14001	44.39136238	46.9
17.30	221.143	95.5	2.13276	17.9415	32.56321863	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	41.32157	3.37695	38.4	37.20764	125.6484	
9.30	40.02472	5.207262	38.4	35.7192	185.9992	
10.30	39.20771	6.17815	38.4	34.84988	215.3078	
11.30	38.81932	6.57765	38.4	34.43459	226.4987	
12.30	38.63556	6.752217	38.4	34.23631	231.171	
13.30	38.66777	6.66225	38.4	34.26195	228.2617	
14.30	38.95241	6.2181	38.4	34.54585	214.8096	
15.30	39.21524	5.984106	38.4	34.83378	208.449	
16.30	40.00322	4.769494	38.4	35.66582	170.1079	
17.30	41.12392	2.078744	38.4	37.33359	77.60698	

Table no. 3: March metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	477.258	144.258	1.97359	17.19712	43.54861	46.9
9.30	651.581	175.258	1.88799	16.53843	53.26947	46.9
10.30	740.516	195.903	1.71072	16.17852	58.58087	46.9
11.30	793.194	205.581	1.62719	15.95623	61.86147	46.9
12.30	809.871	211.065	1.66269	15.86115	63.26463	46.9
13.30	795.71	214.613	1.76408	15.87842	63.00969	46.9
14.30	764.645	205.29	1.92092	15.98239	61.47539	46.9
15.30	702	187.129	2.06621	16.19834	58.28845	46.9
16.30	583.29	164.065	2.20565	16.57299	52.75933	46.9
17.30	338.29	110.065	2.30668	17.26553	42.53906	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	40.11211	4.486225	38.4	35.78465	160.538	
9.30	38.85293	6.124861	38.4	34.414	210.7891	
10.30	38.14416	6.96085	38.4	33.6651	234.3377	
11.30	37.70584	7.456024	38.4	33.20253	247.5589	
12.30	37.52554	7.612787	38.4	33.00469	251.2577	
13.30	37.57215	7.479674	38.4	33.04063	247.1332	
14.30	37.78435	7.187663	38.4	33.25697	239.0399	
15.30	38.21959	6.5988	38.4	33.70633	222.4213	
16.30	38.96467	5.482926	38.4	34.48593	189.0838	
17.30	40.14735	3.179926	38.4	35.92699	114.2452	

Table no. 4: April metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	498.9	178.7	1.90686	16.75567	50.0633875	46.9
9.30	628.867	208.933	1.77132	16.2143	58.05283513	46.9
10.30	721.667	223.7	1.55023	15.82902	63.73883513	46.9
11.30	762.467	232.367	1.45889	15.61863	66.84373513	46.9
12.30	778.433	236.4	1.50725	15.51478	68.37620238	46.9
13.30	769.6	233.167	1.64357	15.5168	68.3465	46.9
14.30	737.367	224.3	1.8473	15.62147	66.80182263	46.9
15.30	674.067	204.833	2.05529	15.84022	63.57348513	46.9
16.30	549.333	183.833	2.23743	16.22956	57.82768988	46.9
17.30	309.867	138.133	2.37862	16.88894	48.09671013	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	39.31664	4.68966	38.4	34.86606	163.51	
9.30	38.3082	5.91135	38.4	33.73955	199.4463	
10.30	37.56803	6.78367	38.4	32.93782	223.4393	
11.30	37.16974	7.16719	38.4	32.50003	232.9339	
12.30	36.97728	7.31727	38.4	32.28396	236.2304	
13.30	36.9894	7.23424	38.4	32.28814	233.5802	
14.30	37.19813	6.93125	38.4	32.50594	225.3068	
15.30	37.62608	6.33623	38.4	32.96114	208.8493	
16.30	38.36832	5.16373	38.4	33.77133	174.3859	
17.30	39.37743	2.91275	38.4	35.14336	102.3638	

Table no. 5: May metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	442.032	205.774	2.42927	16.69507	50.95772	46.9
9.30	555.29	242.29	2.34528	16.23419	57.75933	46.9
10.30	651.645	258.097	2.29812	15.85813	63.30912	46.9
11.30	697.839	266.71	2.3399	15.64283	66.48646	46.9
12.30	705.419	271.419	2.47075	15.55976	67.7125	46.9
13.30	702.839	264.258	2.67558	15.54954	67.86323	46.9
14.30	669.355	253.097	2.93334	15.6564	66.28626	46.9
15.30	602.387	232.161	3.16436	15.87608	63.04431	46.9
16.30	494.29	198.806	3.34653	16.21717	58.01056	46.9
17.30	258.581	159.581	3.48132	16.84324	48.771	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	39.19373	4.155101	38.4	34.73996	144.348	
9.30	38.3755	5.219726	38.4	33.78093	176.327	
10.30	37.67192	6.125463	38.4	32.99841	202.136	
11.30	37.26688	6.559687	38.4	32.55041	213.526	
12.30	37.11763	6.630939	38.4	32.37754	214.693	
13.30	37.10179	6.606687	38.4	32.35628	213.767	
14.30	37.3093	6.291937	38.4	32.57864	204.982	
15.30	37.72663	5.662438	38.4	33.03575	187.062	
16.30	38.34313	4.646326	38.4	33.74551	156.792	
17.30	39.13389	2.430661	38.4	35.04828	85.1904	

Table no. 6: June metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	348.633	215.433	3.63419	17.12447	44.62073	46.9
9.30	465.167	263.2	3.5738	16.72735	50.48145	46.9
10.30	504.233	293.667	3.5694	16.52536	53.48888	46.9
11.30	561.5	293.333	3.61031	16.32681	56.39246	46.9
12.30	588.6	300.133	3.71162	16.22824	57.84713	46.9
13.30	534.367	301.867	3.86526	16.33003	56.3449	46.9
14.30	516.2	298	4.06368	16.39222	55.42718	46.9
15.30	464.367	267.933	4.25969	16.55519	53.02215	46.9
16.30	409.367	219.867	4.41881	16.75215	50.11541	46.9
17.30	261.9	164.733	4.48814	17.15312	44.19801	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	39.89847	3.27715	38.4	35.63348	116.7763	
9.30	39.26178	4.37257	38.4	34.80712	152.1965	
10.30	38.89879	4.73979	38.4	34.38307	162.9685	
11.30	38.53881	5.2781	38.4	33.97366	179.3164	
12.30	38.35441	5.53284	38.4	33.76856	186.836	
13.30	38.55002	5.02305	38.4	33.98037	170.6851	
14.30	38.66255	4.85228	38.4	34.10977	165.5101	
15.30	38.94817	4.36505	38.4	34.44888	150.3711	
16.30	39.27661	3.85306	38.4	34.85873	134.3128	
17.30	39.74677	2.46186	38.4	35.69308	87.87137	

Table no. 7: July metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	182.935	207.71	3.48	17.81	34.51	46.9
9.30	261.581	275.419	3.35	17.57	38.01	46.9
10.30	307.065	306.323	3.24	14.41	40.32	46.9
11.30	359.065	312.613	3.19	17.26	42.53	46.9
12.30	336.516	331.774	3.22	17.28	42.18	46.9
13.30	370.806	321.161	3.31	17.21	43.28	46.9
14.30	287.387	312.548	3.47	17.42	40.51	46.9
15.30	271.323	270.416	3.61	17.46	39.54	46.9
16.30	211.806	197.387	3.59	17.63	37.04	46.9
17.30	146.548	135	3.58	17.82	34.23	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	4.066	1.719	38.4	37.05	63.72	
9.30	40.55	2.458	38.4	36.56	89.98	
10.30	40.37	2.886	38.4	36.23	104.62	
11.30	40.17	3.375	38.4	35.92	121.26	
12.30	40.18	3.16	38.4	35.97	113.82	
13.30	40.09	3.485	38.4	35.82	124.86	
14.30	40.32	2.701	38.4	36.21	97.825	
15.30	40.38	2.554	38.4	36.34	92.76	
16.30	40.48	1.999	38.4	36.7	73.072	
17.30	40.43	1.377	38.4	37.09	51.104	

Table no. 8: August metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	219.38	197.83	2.868	17.84	33.92	46.9
9.30	316.58	256.16	2.823	17.57	37.93	46.9
10.30	340	300.96	2.75	17.47	39.51	46.9
11.30	357.74	327.87	2.72	17.39	40.6	46.9
12.30	420	320.19	2.75166	17.25	42.74	46.9
13.30	346.581	348.38	2.8263	17.4	40.55	46.9
14.30	333.51	319.12	2.98	17.44	39.93	46.9
15.30	361.77	275.774	3.05	17.41	40.39	46.9
16.30	214.387	216.581	2.976	17.75	35.38	46.9
17.30	113.12	129.613	2.92	18	31.64	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	40.93	2.06	38.4	37.14	76.59	
9.30	40.69	2.97	38.4	36.57	108.844	
10.30	40.53	3.19	38.4	36.35	116.184	
11.30	40.41	3.36	38.4	36.19	121.73	
12.30	40.202	3.94	38.4	35.89	141.72	
13.30	40.411	3.25	38.4	36.2	117.956	
14.30	40.47	3.13	38.4	36.29	113.78	
15.30	40.45	3.4	38.4	36.22	123.2	
16.30	40.72	2.01	38.4	36.93	74.434	
17.30	40.44	1.06	38.4	37.462	39.838	

Table no. 9: September metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	280.233	162.233	2.07	17.73	35.59	46.9
9.30	378.96	222.333	2.06	17.43	39.98	46.9
10.30	418.3	265.2	2	17.29	42.05	46.9
11.30	431.73	273.567	1.96	17.233	43.01	46.9
12.30	437.73	285.3	1.97	17.2	43.44	46.9
13.30	437.63	269.633	2	17.20327	43.456	46.9
14.30	423.6	263.3	2.04	17.246	42.81	46.9
15.30	356.233	225	2.049	17.4	40.39	46.9
16.30	311.033	166.8	1.94	17.535	38.55	46.9
17.30	131.86	94.266	1.86	17.96	32.26	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	40.92	2.63	38.4	36.9	97.21	
9.30	40.51	3.56	38.4	36.28	129.346	
10.30	40.28	3.93	38.4	35.99	141.599	
11.30	40.017	4.05	38.4	35.85	145.58	
12.30	40.12	4.11	38.4	35.79	147.49	
13.30	40.1	4.113	38.4	35.7	147.3	
14.30	40.19	3.98	38.4	35.88	143	
15.30	40.44	3.34	38.4	36.22	121.38	
16.30	40.6	2.92	38.4	36.48	107.188	
17.30	40.57	1.23	38.4	37.37	46.46	

Table no. 10: October metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	424.129	155.387	1.262	17.51	38.802	46.9
9.30	569.484	194.065	1.122	17.03	45.992	46.9
10.30	340.194	226.129	1.054	16.73	50.309	46.9
11.30	671.29	241.32	0.977	16.61	52.179	46.9
12.30	670.065	245.19	0.97	16.59	52.449	46.9
13.30	634.774	242.19	1.02	16.67	51.272	46.9
14.30	598.419	226.83	1.11	16.77	49.751	46.9
15.30	514.161	190.64	1.19	16.99	46.571	46.9
16.30	345.742	146.355	1.26	17.37	40.873	46.9
17.30	45.48	55.25	1.333	18.147	29.52	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	40.69	3.98	38.4	36.45	145.33	
9.30	39.775	5.35	38.4	35.44	189.71	
10.30	39.209	6.01	38.4	34.83	209.6	
11.30	38.96	6.31	38.4	34.56	218.126	
12.30	38.932	6.29	38.4	34.52	217.488	
13.30	39.102	5.96	38.4	34.69	207.032	
14.30	39.3	5.62	38.4	34.9	196.37	
15.30	39.73	4.83	38.4	35.35	170.89	
16.30	40.37	3.24	38.4	36.16	117.89	
17.30	39.32	0.42	38.4	37.76	16.145	

Table no. 11: November metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8:30	387.64	105.903	2.32	18.16	29.2	46.9
9:30	578.129	148	1.96	17.52	38.67	46.9
10:30	668.387	147.355	1.9	17.06	45.5	46.9
11:30	710.194	190.484	1.92	16.8	49.27	46.9
12:30	739.194	193	1.71	16.67	51.22	46.9
13:30	722.452	190.806	1.58	16.69	50.92	46.9
14:30	671.194	176.71	1.62	16.83	48.86	46.9
15:30	562.742	157.129	1.72	17.13	44.64	46.9
16:30	342.387	117.29	1.95	17.73	35.58	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8:30	41.86	3.64	38.4	37.8	137.76	
9:30	40.63	5.43	38.4	36.47	198.2	
10:30	39.73	6.28	38.4	35.5	223.09	
11:30	39.24	6.67	38.4	34.97	233.502	
12:30	38.48	6.94	38.4	34.7	241.121	
13:30	39.04	6.79	38.4	34.74	235.95	
14:30	39.34	6.3	38.4	35.05	221.04	
15:30	39.96	5.28	38.4	35.65	188.06	
16:30	41.03	3.21	38.4	36.9	118.78	

Table no. 12: December metrological data (2016) and PV parameter.

Time of day	Beam irradiance	Diffuse irradiance	Wind speed	Efficiency	Cell temperature	Voc Ref
8.30	387.64	105.903	2.32	18.16	29.2	46.9
9.30	578.129	148	1.96	17.52	38.67	46.9
10.30	668.387	147.355	1.9	17.06	45.5	46.9
11.30	710.194	190.484	1.92	16.8	49.27	46.9
12.30	739.194	193	1.71	16.67	51.22	46.9
13.30	722.452	190.806	1.58	16.69	50.92	46.9
14.30	671.194	176.71	1.62	16.83	48.86	46.9
15.30	562.742	157.129	1.72	17.13	44.64	46.9
16.30	342.387	117.29	1.95	17.73	35.58	46.9
Time of day	**Voc**	**Imp**	**Vmp Ref(Vdc)**	**Vmp**	**Pmp**	
8.30	41.86	3.64	38.4	37.8	137.76	
9.30	40.63	5.43	38.4	36.47	198.2	
10.30	39.73	6.28	38.4	35.5	223.09	
11.30	39.24	6.67	38.4	34.97	233.502	
12.30	38.48	6.94	38.4	34.7	241.121	
13.30	39.04	6.79	38.4	34.74	235.95	
14.30	39.34	6.3	38.4	35.05	221.04	
15.30	39.96	5.28	38.4	35.65	188.06	
16.30	41.03	3.21	38.4	36.9	118.78	