DESIGN of a HYBRID POWER GENERATION SYSTEM USING
SOLAR-WIND ENERGY

by

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MTECH-ENERGY SYSTEMS

Submitted in fulfilment of the requirements for the degree of
Master of Science (Research)

Deakin University
November 2018

submitted for the degree of Master of Science (Research)

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ACKNOWLEDGEMENT

It is a great pleasure for me to acknowledge all those who have advised and helped me wholeheartedly to lead my project to the success. First, I would like to thank GOD almighty for the blessings with grace and taking this to a successful completion.

I would like to express my sincere gratitude to my supervisor Dr. Aman Maung Than Oo for his support and guidance throughout the discussions of the project. His academic talent and research expertise helped me a lot in various stages of the research work. I consider this as one the most valuable opportunity in my career to work with such a professor on completing this project successfully.

I am thankful to my unit chair Dr. Jim Rookes for the valuable advice support and feedback provided to me in various levels of the research work which helped me to complete the project.
ABSTRACT

Renewable energy is an alternative solution for power generation in the day today life. Power generation from conventional energy is having a drastic effect to the environment and the ecological life of humans. The energy from renewable sources are abundantly available over the universe. Energy from renewable sources are clean, ecofriendly, efficient and reliable. Solar and wind are gaining much importance in the present world. The project aims to develop a grid connected hybrid power generation system using solar and wind energy in the Matlab/Simulink software. The model is designed based on the availability of solar irradiance, sunshine hours, temperature, wind speed, wind direction and topography. Based on the datas, a model can be developed combining the energy from solar and wind resources. An average solar irradiance of 5.68KW/m²/day and wind speed of 12.9mph is available over the parts of Kerala. The average temperature range in the parts of Kerala is 28°C since it is located in between Tropic of Cancer and Equator. Standalone models for a PV and wind is also simulated. The hybrid model consists of solar panels, (P&O) MPPT, boost converter, inverter, wind turbine, PMSG generator all connected to a grid. Under different irradiance and temperature conditions the PV model is simulated, and output is observed. The hybrid model is simulated, and the Matlab results are analyzed.
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LIST OF ABBREVIATIONS

GW             Gigawatt
MW             Megawatt
KWh            Kilowatt Hour
NTPC           National Thermal Power Corporation
KSEB           Kerala State Electricity Board
CIAL           Cochin International Airport Limited
MPPT           Maximum Power Point Tracking
MATLAB         Matrix Laboratory
PV              Photo Voltaic
DC              Direct Current
AC              Alternative Current
MPP             Maximum Power Point
UPQC            Unified Power Quality Conditioner
DVR             Dynamic Voltage Restoration
SVC             Static Var Compensator
STATCOM         Static Synchronous Compensator
PWM             Pulse Width Modulation
IGBT            Insulated Gate-Bipolar Transistor
P&O             Perturb and Observe
IC              Incremental Conductance
VSI             Voltage Source Inverter
CSI             Current Source Inverter
PCC             Point of Common Coupling
PMSG            Permanent Magnet Synchronous Generator
IG              Induction Generator
THD             Total Harmonic Distortion
CHAPTER 1
INTRODUCTION

Energy is an important factor for the human development and a reason influencing the global prosperity. It supports the economic growth, human welfare and the quality of life of a nation. The energy from conventional source has major drawbacks to the present and future ecological balance and safety both locally and globally. It’s a known fact that the world’s existing main energy resources will be depleted in a few years’ time. Therefore, in today’s energy demanding world, renewable energy sources which is clean, non-polluting and ecofriendly is a better option. Renewable energy is a continuous form of energy available in plenty from the natural sources such as sunlight, wind, rain, waves, geothermal heat and tides. Energy generated from the natural sources are carbon free with less pollution and capable enough to compensate the energy generated from coal and other fossil fuels thus preserving these resources for the future generation. (Preeti H. Narnaware 2015)

1.1 Need for Renewable Energy

In the present world, the need for electrical energy is increasing very rapidly. The excessive use of conventional sources such as coal, petroleum, oil and other by products for energy has led to drastic depletion of these resources and major impacts to the environmental conditions such as greenhouse gas emission which causes an imbalance in the ecosystem. At the same time with the existing conventional energy sources the needs cannot be met. Therefore, an alternative means of energy is from non-conventional energy sources which plays an important role in meeting the demands of the world and these renewable energy sources are clean, ecofriendly and reliable for energy generation. (Atiq and Soori 2016)

The most prominent forms of renewable energy are from solar, wind, hydro and biomass. These resources are abundantly available in the nature. The only drawback of these renewable means of energy is the variation in the seasonal and natural climatic conditions. During summer season, the solar energy is capable in generating energy while only at the times of winter and spring the production of energy from sun is low. Similarly, the energy from wind varies due to change in the wind speed and it cannot give a consistent output. Therefore, for a continuous balanced supply of
power a hybrid power generation using the renewable energy is more effective. A Hybrid power system is a combination of two or more renewable energy sources combined in an effective manner for a continuous energy generation to meet the load demands. This system is more reliable and efficient being environmental friendly with low cost. The most widely utilized renewable form of energy for the generation of electricity is from solar and wind power. There are several advantages of combining the solar and wind power the overall peak demand can be reduced, the dependency on single source for power in many situations is significantly reduced thereby the quality of power produced is improved. (Bogaraj and Kanakaraj 2012, Katti 2012, Ali, Aridhi et al. 2016)

1.2 Renewable Energy in India

India stands amongst the leading positions in the world market for power generation from the renewable energy. Indian power sector plays a major role in the field of non-conventional energy thus meeting the growing demands and energy needs. The Indian government has a target to achieve a 175GW of energy from the installed renewable capacity by the year of 2022 among which 60GW is the energy from wind and 100GW is the energy from sun. India stands in 4th and 6th position in the world market for an installed capacity of wind and solar power. As per the studies, by November 2017 India had a total of 62GW from the installed capacity of renewable energy. India estimates to have an installed capacity of 1096GW potential from the renewable energy of which 750GW from the solar power, 300GW from wind power, 21GW from small hydro power and 25GW from bioenergy on a commercial basis. The reports reveal that India has a total output of 331.95GW of power from all the resources among which the contribution from renewable energy is 60.98GW which is 18.37% of the total installed capacity. (Aggarwal and Nijhawan 2016, Pib.nic.in 2018)

To meet the energy demands India depends on conventional and non-conventional sources of energy. It is the duty of the country to meets the growing needs at a reasonable and reliable ways. India has a wide access to all means of energy sources both renewable and non-renewable. The main source of power generation in India is from thermal energy which is around 67 percent of the total installed capacity by 2017. Renewable energy stands in second position in contributing power to the total capacity of generation and hydro stands in the third position. (Kerennis.nic.in 2018)
India is in the region between Tropic of cancer and the Equator. In India on an average the range of temperature varies between 25°C to 27.5°C and has a high potential of solar radiation. India has a dense population and the insolation of solar is very high with an average of 5KW h per square meter in a day and a total of 2300 to 3200 hours of radiation in a year in almost every part of India. The radiation from sun is more in the parts of south/east coast in India. Like sunshine India has a good potential for wind energy and is one of the fastest growing energy sector in the world. The kinetic energy of wind is called wind energy and the conversion of this wind energy to useful form is termed as wind power. The country is blessed with coastal lines and territorial water over several miles into the sea. In the world of energy market India stands as the 3rd largest in the field of wind power for both commercial and domestic purposes. (Khare, Nema et al. 2013)

The southern part of India which includes Kerala, Andhra Pradesh, Karnataka, Tamil Nadu is capable enough for producing solar and wind power. The state Kerala also has the power generation from energy sources such as solar, wind, hydel and thermal. The main contributor of power generation in Kerala is from thermal and hydro along with this, solar and wind also contributes in small percent. Kerala’s main power generation is from hydro power and the state fully depends on hydro power for electricity. If there is a shortage in rainfall during the monsoon season it leads to power crisis. The other source of power contributor to the total installed capacity are thermal energy from NTPC and the wind farm.(Kerennis.nic.in 2018)

The below figure 1.1 details about the total installed capacity of power in Kerala in the year 2017. In the year 2017 the energy generation in Kerala state reached to 2961.11MW in which hydel power was the main contributor with 2107.96MW, thermal power with 718.46MW, 59.27MW from wind energy and 75.42MW from the solar power. The report says that the total solar power capacity over the state includes 13MW from KSEB (Kerala State Electricity Board) and 21.5MW from CIAT (Cochin International Airport Ltd). The overall capacity of solar energy generated on commercial and industrial basis in the state is 120MW. The studies done by KSEB points out that the Kerala state has a potential to produce about more than 1000MW wind power.(Rajwi 2017, Kerennis.nic.in 2018)
1.3 Motivation

The excess demand for the energy from conventional sources has resulted in depletion and drastic environmental issues. Therefore, need of alternative solution to meet the demand without causing any consequences to human and the ecosystem is necessary. The best solution to overcome these concerns is depending upon the natural resources of energy. Natural resources are mainly the renewable energy from the sun, wind, rain, tides and the waves. It is abundantly available in the earth. The proper and efficient utilization can meet the world’s necessity. The most widely used renewable energy source for power generation is from solar and wind. It has high potential and available in plenty. Several studies are conducted individually in utilizing these resources for power generation and still research is in progress. To have a continuous and reliable power supply a hybrid power generation is a best solution.

1.4 Scope of the Project

i. The hybrid system with solar and wind energy is applicable for power generation in both rural and urban areas.

ii. The hybrid system maintains a continuous supply of power.

iii. Hybrid systems utilizing energy from nature can overcome the drawbacks caused due to unfavorable climatic conditions in the environment.
Energy from Solar and wind for power generation is a promising solution pleasing the demands of both the rural and urban population. Utilizing the renewable energy can overcome several issues in the environment like environmental pollution, degradation of fossil fuels leading to global warming can be reduced therefore, the ecological balance and climatic conditions can be maintained.

1.5 Problem Identification

The conventional energy sources are being depleted and causing severe negative impacts to the ecosystem thus exploiting the future needs. Renewable energy plays a vital role in sustaining these conventional sources. The renewable energy is abundantly available in the nature but without proper control and incorporation these resources cannot be used for power generation. The non-conventional energy sources are based on the weather conditions. Depending upon a single source of energy for power generation causes several limitations in the performances. Main drawback on depending on a single source of energy is the unstable operation caused due to inaccessibility and climatic variations. Solar and wind has high potential and is available in plenty in the atmosphere but due to variation in weather, this hybrid power generation system faces the issue of improper and unstable utilization of the accessible sources. Other challenge faced in integrating a renewable energy source for power generation is power quality issues like voltage sag, voltage dip, harmonics, power fluctuations, transients etc. (Aggarwal and Nijhawan 2016)

1.6 Objective of the Project

The primary objective of the project is to utilize the available renewable energy in the nature without causing any harmful effects to the human lives and environment. The main objectives of the project include:

i. To conduct a feasible analysis of the solar and wind availability in nature to develop an alternative solution to the existing power generation system.

ii. To develop a grid connected hybrid solar and wind model using a Matlab/Simulink.

iii. To utilize the maximum available energy for the power generation using controlling techniques.
CHAPTER 2

LITERATURE REVIEW

The ultimate source of energy for power generation is from non-renewable sources of energy such as fossil-fuels. The alternate way to preserve these resources is to depend fully on the renewable sources available in plenty. This research aims in developing a hybrid system utilizing the solar and wind power available in nature to meet the energy demands of the world.

The paper aims in describing the techniques involved for controlling and tracking of maximum power from solar and wind energy. Here the system includes a solar, wind, power converters and a battery. Explains five possible types of results the renewable energy sources can produce and how it can be utilized and charged to a battery. This paper also points out the advanced methods to develop a stable power supply and energy storage. The basic idea behind the system is to have a control over the source of power generated to be supplied to grid or to the battery for storage. (Shen, Izadian et al. 2014)

Fig 2.1: The Proposed Hybrid System for Solar and Wind Power System (Shen, Izadian et al. 2014)
The figure 2.1 details about the proposed hybrid system for the solar and wind power. This hybrid system utilizes both solar and wind power for power generation and alternately have a control of the energy supplied to battery with the help of converters. This system helps to maintain a stable and reliable power supply with desired rating to charge the battery and power the load. Maximum power tracking is done with the help of perturb and observe method for both solar and wind power source. Two branches which are connected in parallel to supply to load and to battery. Both the power sources are controlled by MPPT and voltage source converters. In solar, the MPPT is achieved by varying the controller and regulating the converters. The solar irradiance is efficient under standard conditions of temperature 25°C and irradiance of 600W/m²-1000W/m². The wind energy system has a generator and a turbine for converting the mechanical power to electrical energy. This system includes a variable speed wind turbine and a permanent magnet synchronous generator. Maximum speed is obtained under maximum rotor speed by the MPP. For a supervisory control system, to set the dc and to maintain the power sources and storage system. The control system charges and discharges the battery in accordance with setting the voltage at specified range. When one of the sources is voltage controlled other will be current source.(Shen, Izadian et al. 2014)

The paper focus in development and design of a hybrid system utilizing the solar and wind energy sources with the help of a microcontroller. This model is mainly adopted for domestic purpose applications. Photovoltaic cells help to convert the solar energy into electrical energy or heat energy. This system is mainly of two types one is line dependent and line independent. The line dependent system is not in need of batteries for storing energy. It directly supplies the energy to the demand with the help of an inverter. This line system is also used at times of low sun beam. The line independent system, as the absence of line electricity batteries or accumulators are required for supplying energy at times of demand. The dc output needs to be converted to ac for supplying to electrical appliances. The wind energy is based on the capacity for producing power.(Fesli, Bayir et al. 2009)
The figure 2.2 depicts the block diagram for a hybrid system with micro-controller. During summer, sun beams are enough to produce power while during winter wind velocity is sufficient for power production. The system is designed in a way to supply continuous power and charge the battery sufficiently with the incoming power depending on the available source with the help of a control system. For solar radiations available, the MPPT system helps in tracking the solar energy ensuring high power generation. Real time control system controls the storage usage of electricity. The control card, measurement card and connection card manage the supply of electricity to batteries. The microprocess is controlled by control card managing the data coming from all the sources at real time while the current and voltage of wind, solar and inverter is measured using the measurement card. For an implemented system control card decides whether the system should be involved or not. Current sensors and voltage sensors were used in real time control system for the input and output values. (Fesli, Bayir et al. 2009)
This paper details about a solar-wind hybrid power generation system which is becoming economical on considering the life cycle cost and the environmental benefits. Hybrid systems have an advantage of maintaining a balanced system with uninterrupted power supply from any of the sources. The energy produced by this combination is fed to a hybrid controller. Then it is supplied to a battery for load requirements. The hybrid controller used here is a microcontroller. This controller has a control over the voltage generated by solar and wind to be fed to the battery. The figure 2.3 is the flow chart for a system sizing. This system is supported by a relay which gives an alarm when an over current or over voltage is detected. This paper also summaries the details regarding the life cycle cost of a hybrid system such as initial capital cost, replacement cost for a battery and maintenance and operation cost.\cite{Katti2012}

![Flow Chart for System Sizing](image)

**Fig 2.3: Flow Chart for System Sizing\cite{Katti2012}**

This paper details about the sizing procedure developed for a hybrid system involving solar and wind energy. The sizing technique was developed as mathematical models which can meet the performances of hybrid solar and wind system with reducing technical obligations with lowering the energy costs. The main system input includes load, average radiation from solar energy, wind resource and temperature. The system is modelled using MATLAB software. Using optimization technique, iteration was done for sizing and output results are obtained. Using the available data of weather conditions, the sizing and different strategies for the operation of the hybrid system is simulated. This hybrid PV-wind system had a considerable decrease over the emission of
greenhouse gases and huge amount of energy production. The battery is charged and discharged based upon the output from hybrid solar and wind source. To avoid overcharging of battery and to protect it the system is disconnected from the source when voltage reaches a point. Similarly, if the required current is not delivered by the source to load the system is connected to battery. The PV system can be connected either in series or parallel to produce the required current and voltage. The solar energy output that is current and voltage depends mainly on temperature and solar irradiance. The wind energy systems are connected in parallel to obtain the desired output. They are never connected in series. In most cases parallel strings of two different wind turbine types are operated together in one system to form the system output. (Engin 2013)

This paper describes about the hybrid PV-wind system connected to grid and the techniques involved for maximum power tracking in wind and solar. In wind energy system, variable speed wind turbines along with permanent magnet synchronous generator is used. This system provides high reliability and efficient output without the help of any external support. There are dc link converters connected to grid to maintain constant voltage. In PV systems, the load is connected directly to grid. The whole system is examined using the MATLAB software. (Gowtham and Royrichard 2014)

Fig 2.4: Block diagram for a wind energy conversion system (Gowtham and Royrichard 2014)

The above figure 2.4 is the block diagram for a wind energy conversion system. In a wind turbine system for energy conversion, the system has a permanent magnet synchronous generator, a three-phase rectifier, a boost converter used to control the optimum torque tracking is connected to dc system which is further connected to grid through an inverter. The main purpose of optimum torque
tracking in wind energy conversion system is to attain maximum power from wind turbines. It also measures the speed produced, reference torque generated and the reference DC. The reference torque is compared with the calculated torque. If the reference torque is less than measured torque the generator speed will increase. If the reference torque is higher than the measured torque the generator speed is decreased.

Fig 2.5: Block diagram for PV energy conversion system (Gowtham and Royrichard 2014)

The above figure 2.5 is the block diagram for a PV energy conversion system. The PV system for energy conversion includes a PV array, incremental conductance for MPPT to control the boost converter connected to dc network. This dc network is connected to grid through an inverter. The incremental conductance method is used for maximum power point tracking of the PV arrays. The terminal voltage of PV arrays is always maintained with the MPP voltage obtained. To operate the PV array at maximum power, point the ratio change in output conductance is made equal to the negative output conductance.

Grid converter for a hybrid system is done to perform a link between the dc bus and the ac grid which is further connected to load for supply. The controller in the system gives a constant output and voltage is maintained at the point of coupling. The inverter works to provide a constant current to the grid. To provide an uninterrupted power supply the controller ensures the stability of system. (Gowtham and Royrichard 2014)

The paper highlights the different methods used for maximum power point tracking in hybrid solar wind system with the perturbation tracking algorithm. Due to DC/DC charging unit, the whole
circuit and control unit is simplified. With the maximum power point tracking technique, the output from the solar and wind is separately controlled. Due to control methods, the system becomes complex and the production cost is high therefore, the total output production is controlled by MPPT tracking at maximum power point. By recognizing the maximum power from wind or solar the MPPT algorithm tracks accordingly. This is simulated in MATLAB software for various tracking of maximum power. The MPPT techniques allows the system to work near to the maximum power point. For wind, tip speed ratio control, power signal control methods are used to have MPPT while in PV systems, observation perturbation method, constant voltage control method and incremental conductance methods are used to attain the MPPT. The simulation results apply not only for the controlling methods of the hybrid solar-wind system but also the output current of the system is stable and reliable. The impact of overcharging on batteries are reduced. (Huang, Xu et al. 2011)

Paper studies about the availability of solar and wind resource in India. The major drawback in implementing the solar and wind resource is the intermittency. This is mainly because of the varying climatic conditions. Sudden variations in the energy supply leads to destabilization of the grids causing interruption in the power supply. The problem of intermittency can be solved by choosing the geographical area where the availability of the one resource or the other is in abundant. Study aims in finding the site where the resource is available in plenty and the power to grid can be met without the intermittency. (Lolla, Roy et al. 2015)

Solar resources are accessed in the downward direction while wind in the eastward and westward direction. It was observed that solar energy is available throughout the year in all the grids while wind energy is available partly in a year only in southern and western grids of India. The variability in wind energy can be overcome by solar energy cycle for supply. The solar cycle is high throughout the year and is low only during winter in India. The peak solar availability is in the month of March in southern parts of India. The peak wind resource is available during monsoon season because of heavy winds from southern and western parts. Very little wind energy is available in India throughout. The studies analyses the southern grids as the most renewable energy availability followed by the western, eastern and northeastern grids. The northern grids are facing major issue in power supply from renewable energy due to need of large farm lands for deployment. In these areas, the solar and wind can meet the demands with less disruption in supply.
Apart from intermittency other issue is the cost of developing these renewable energy systems. Solving these factors in future a promising power system network from renewable energy can be developed. (Lolla, Roy et al. 2015)

This paper describes about the renewable energy source in India and details about the solar and wind power target the country is about to achieve in the year 2022. This paper also points out the power quality issues the power sector faces on combining renewable energy sources for energy generation. The main reason to depend on renewable energy for power generation is high demand and exhausting of other natural resources due to continuous use. The solar and wind energy are combined to form a hybrid system which is integrated to grid for the generation of power by the converters to convert the DC power to AC power. Due to variation and unavailability of power, it may result in unstable operation, power fluctuations, transients, faulty conditions. Therefore the use of power electronic devices and depending on renewable energy these integration can lead to power quality issues. (Aggarwal and Nijhawan 2016)

The potential of solar radiation in India on an average annual temperature is in the range of 25°C -27.5°C. As per the studies India has an approximate of 750GW of solar power. Photovoltaic modules are mounted along with other power generating equipment to generate AC power to the grid. Solar power is a better solution to area where rural energy supply is impossible. It was found that about 1KW solar power for houses will result in 170pounds of cola from burning, 300pounds of carbon-dioxide released to the atmosphere and 150 gallons of water used. Presently, the cost of installing solar for power is higher than other choices but it has several advantages. It is eco-friendly, portable, easy to handle and cost-effective. (Aggarwal and Nijhawan 2016)

The most widely used renewable energy after solar for power generation is wind. It has a vast potential and varies based on the area. India stands has the world’s fifth largest installed wind capacity. The estimation of total wind potential is about 302GW if the tower height is about 100m. wind energy is higher in remote area that in developed parts and energy from wind backs the electrification for rural consumers. The drawback of this system other than wind availability is large area for implementation. Comparing to solar power systems the installation of wind power system is less. An issue faced on integrating solar and wind for power generation is power quality issues. It is mainly due to the variations in voltage, current and frequency. Normally, to overcome these problems devices such as STATCOM and SVC being used to avoid disturbances and faults.
While to overcome the voltage and current disturbances STATCOM, DVR AND UPQC are used. To improve the quality and balance the load at distribution side DSTATCOM are used. these devices plays an important role between consumer products and grid system to improve the quality of power.(Aggarwal and Nijhawan 2016)

The papers details about the approach taken to model a 10.44kW grid connected PV module using Matlab/Simulink software. The model was designed using PV panels, boost converter, Inverter, Maximum Power Point Tracker and an LC filter. The PV module was designed and developed using the basic equations. The PV module used here is 24 sun power 435W panels(SPR-435NE-WHT-D) and values are available in the datasheets. Based on current values the PV module is designed using various subsystems such as photon current, diode current, reverse saturation current at reference temperature, reverse saturation current. (Atiq and Soori 2016)

For the complete modelling of solar PV system, it includes the MPPT of incremental conductance with internal regulator, a boost converter to boost up and regulate the DC output power of PV array, an inverter to convert the DC into AC output for that a three phase three level voltage source converter is being used. The inverter is controlled using the gate signal in the IGBT during its ON and OFF period. An inverter control loop is designed to generate the signals. With the help of these loops controlled PWM signals are generated and the IGBT switches in inverter is controlled. Thus, giving an output of three phase sinusoidal voltage and currents. To reduce the harmonics of inverter current LC filters are used at the output of inverter. The model designed with PV array connected to grid is observed for varying temperature and solar radiations. The studies say solar radiation has much more affect than temperature on the power output. At times of high irradiance, the output from inverter is higher than load demand therefore power flows to grid whereas at low irradiance if output is less grid supplies power. (Atiq and Soori 2016)

The paper focus on developing a hybrid wind/PV system in Matlab/Simulink to meet the energy demands. This paper studies and demonstrates a model of hybrid solar-wind model connected to a grid for supplying power. In solar PV system the sunlight is directly captured using the solar panels and converted to electricity. The solar PV panels are made using solar cells of semiconductor materials. PV cell is a semiconductor diode where its p-n junction is exposed to light. As the light strikes the junction of a cell, holes and electrons are generated thus current is produced which is supplied to load once short circuited. The solar panels are made by combing many PV cells and
depending upon the requirement the solar cells are either connected in parallel or series. For high output current the PV cells are connected in parallel with the circuit while to achieve high voltage output the cells are connected in series with the circuit. (Anjali Rana 2015)

Based on the mathematical equations the PV model is made in Simulink. The PV cells directly converts the solar energy into electricity. It has output characteristics such as I-V and P-V. The system works under standard conditions of temperature 28°C and solar irradiance of 1000W/m². The system includes the calculation of short circuit current, open circuit voltage, current at maximum power, voltage at maximum power, and photon current which altogether forms complete model of PV array. Wind energy is derived from the moving energy of wind. Kinetic energy is transformed to mechanical energy using wind turbine. The density of air and velocity of wind influence the magnitude of change in mechanical energy. The ideal wind energy model is designed based on three different operating regions with different wind speed and these are cut-in wind speed, rated wind speed and cut-out wind speed respectively. (Anjali Rana 2015)

![Fig 2.6: Power Curve of Wind Turbine](Anjali Rana 2015)

The above figure 2.6 depicts the power curve for a wind turbine. The complete hybrid model is designed to increase the efficiency thus increasing the output energy of the system thus reducing the need for a storage. The hybrid system is more efficient reliable and cost effective comparing to single systems. The generated DC output is converted to AC based on grid frequency with the help of PWM generator and voltage source converter. The simulation of hybrid system is carried and the generated output voltages are supplied to grid. (Anjali Rana 2015)
This paper details about the various MPPT techniques used in hybrid solar wind power generation system connected to a grid. Due to varying weather conditions the generation of solar wind power to the maximum is not possible therefore various techniques are implemented with the design to improve the output power. The most commonly used MPPT techniques for PV systems are Perturb and Observe (P&O), Incremental Conductance method, Open Circuit Voltage and Short Circuit Current. The P&O works at steady state radiations and is accurate. Incremental conductance method is works at varying weather conditions and is efficient and accurate, but the techniques used for controlling the circuit is more difficult. The open circuit voltage and short circuit current both are not applicable for high power generations. To improve the accuracy of PV systems at any varying weather conditions two model MPPT is developed. Based on area and the weather conditions combinations of any MPPT technique is done. The most accurate combination for any climatic condition is incremental conductance method and open circuit voltage. The wind energy system is different and is based on the concepts of generators. To work properly at varying wind speed MPPT technique is used, permanent magnet synchronous generators and a pitch angle-controlled wind turbine would be efficient when comparing to a doubly fed induction generators. The output produced by the solar wind system at the inverter is provided through space vector PWM to avoid distortions and improve efficiency. The below figure 2.7 shows the flow chart for a two-model MPPT.(Reddy, Narayana et al. 2018)

Fig 2.7: Flow chart for a two model MPPT(Reddy, Narayana et al. 2018)
After solar energy the most available source of energy is from wind. Turbines of the wind system are rotated using the kinetic energy from wind to generate mechanical energy and the electrical energy is generated by converting mechanical energy by the generators. This system uses an optimal control technique as the MPPT and output power is enhanced using pitch angle of wind speed. On integrating the PV energy and wind energy systems through an inverter AC output is produced. Space vector pulse width modulation technique is used with inverter to avoid the power quality issues of output power. The result shows that PV system with two model MPPT had higher output voltage and wind system using MPPT resulted in higher output.(Reddy, Narayana et al. 2018)

The paper describes hybrid model of solar wind system connected to grid and analysis of the power quality issues involved. A prototype model of a single-phase power circuit was developed and simulation in Matlab was done along with study of a seven-level inverter. Several methods are developed to reduce the power quality issues and a new approach was to use a multilevel inverter. Multilevel inverters are normally to reduce the harmonic distortion in this paper a H bridge multilevel inverter is used to improve the performance and reduce the power quality issues.(Zade, Gaikwad et al. 2016)

The system consists of solar and wind energy generation connected to grid thus reducing the power quality issues. The model designed mainly focused on solar PV systems output fed through a
multilevel inverter to the grid. The output from solar is dc therefore it needs to be converted to ac before supplying to grid. While the output energy generated from wind is directly supplied to the grid. The multilevel inverter used with PV system acts as a controller at the Point of Common Coupling (PCC) reducing the Total Harmonic Distortions (THD). Under standard conditions the solar PV model is simulated using a controller and without using controller. The results show that the load current, source voltage and source current while plotting with respect to time the source voltage is sinusoidal, and the current from the source and the current from load are same and non-sinusoidal. When the system is simulated using a seven-level multilevel inverter with level shifted carrier pulse width modulation. The output source voltage, source current and load current are in sinusoidal waveforms when using a controller. Controller helps to reduce THD in PV systems. In hardware model designed using hybrid solar and wind for a single phase is developed. The solar PV energy is supplied to grid through a multilevel inverter. This seven-level inverter reduces the voltage sag and swell in the PCC of the system. Power supply unit includes step down transformer, bridge rectifier, filter and voltage regulator. The output voltage is increased with use of controller. (Zade, Gaikwad et al. 2016)
CHAPTER 3

PV ENERGY SYSTEM

Energy captured from the radiation of sun is called solar energy. It is present abundantly over the earth surface and is freely accessible. The energy from sun is pollution free and highly efficient source with low cost. PV panels are used for generating electricity from sun’s energy. Solar panels are used as the medium for the conversion of energy into heat or electricity. The solar panels are made using semiconductor materials. The semiconductor material used in the solar cells are silicon where the sunlight strikes the surface of cell and gets absorbed. Basically, the solar cells functions like diode with PN junction formed in the material. As the sunlight falls over the surface of material energy gets absorbed allowing the electrons to move freely. The flow of electrons results in generation of electric current. The principle used behind the conversation of solar energy to electric power is termed as photo electric effect. (Sivaramakrishna and Reddy 2013, Ingole and Rakhonde 2015)

Solar panels are formed by combining the PV cells. PV cells are connected to form a PV module and PV modules are further interconnected to get the required PV panels or arrays. Usually, PV cells are normally in the range of 36 or 96 cells in a module. Based on the load demands the cells are connected either in series or parallel combination. Like the cell arrangement the modules will also be connected either in series or parallel combinations. For high output voltage the PV cells are arranged in series and for high output current the PV cells are arranged in parallel manner. Initially in a solar panel the cells are connected in series sequence to get the desired voltage and so formed strings are parallelly connected to obtain the desired current. (Sivaramakrishna and Reddy 2013, Ingole and Rakhonde 2015)
Fig 3.1: From PV Cell to PV Module to PV Panel to PV Array.

Fig 3.2: Schematic Diagram of Solar Energy. (Research Gate, 2019)

The figure 3.2 represents the basic schematic diagram for the solar energy production. In the figure the radiation from the sun is made to fall on the solar panels. These solar panels are made from
Photovoltaic silicon semi-conductor materials. Due to the photoelectric effect of PV cells the sun’s energy is directly converted to electricity. The DC output from the solar panels are fed to the input of converters. Maximum Power Point Tracking techniques are used along with the system to track the maximum solar energy and these pulses are supplied to the converter. Converters are used for supplying a regulated DC output by transforming the voltage from one level to other level. The converter takes the input signal from solar panels and gives a controlled DC output. The controlled DC output from converters are fed to the inverter input convert to AC output, which is to be supplied to the grid or the load. The figure 3.3 is the block diagram representation for a solar energy generation.

![Block Diagram of Solar Energy](image)

**Fig 3.3: Block Diagram of Solar Energy**

### 3.1 Modelling of Solar panel

The basic element of a solar panel is the PV cells. The solar panels are designed considering the basic equivalent circuit diagram and the equations of a PV cell. The equations are used to model the PV panel.
The figure 3.4 is the simple diode equivalent circuit diagram for a PV cell using resistor in series and parallel. The generated current by the solar cell can be expressed as

\[ I_{PV \, Cell} = I_D + I_{sh} + I \]

\[ I = I_{PV \, Cell} - I_D - I_{sh} \]  \hspace{1cm} (1)

The diode current for the solar cell is given as

\[ I_D = I_{o \, Cell} \exp \left( \frac{V + I R_S}{a V_{th}} \right) - 1 \]  \hspace{1cm} (2)

\[ I_{sh} = \frac{V + I R_S}{R_P} \]  \hspace{1cm} (3)

Substituting the equations 2 and 3 in 1 it can be written as

\[ I = I_{PV \, Cell} - I_{o \, Cell} \exp \left( \frac{V + I R_S}{a V_{th}} \right) - 1 \] - \frac{V + I R_S}{R_P} \]  \hspace{1cm} (4)

\[ I_{PV \, Cell} = \text{photo current} \]

\[ I = \text{solar cell generated current} \]

\[ I_D = \text{current through the diode} \]

\[ I_{sh} = \text{current flowing through the parallel resistance} \]

\[ R_P = \text{Parallel resistance of PV cell} \]

\[ R_s = \text{series resistance of PV cell} \]

\[ I_{o \, Cell} = \text{Leakage current of current or reverse saturation current} \]

\[ V_{th} = \text{Thermal voltage} \]
\( a \) = diode reality factor

\( k \) = Boltzmann constant \((1.3806503 \times 10^{-23} \text{ J/K})\)

\( T \) = Cell temperature

\( q \) = electron charge\((1.60217646 \times 10^{-19} \text{ C})\). (Anjali Rana 2015)

The terminal voltage:

\[ V_{th} = \frac{KT}{q} \]  

(5) (Atiq and Soori 2016)

Substituting equation 5 in 4

\[ I = I_{PV \text{ Cell}} - I_{o \text{Cell}} \left[ \exp \left( \frac{q(V+IR_s)}{aKT} \right) - 1 \right] - \frac{V+IR_s}{R_p} \]  

(6)

\[ I = I_{PV \text{ Cell}} - I_{o \text{Cell}} \left[ \exp \left( \frac{q(V+IR_s)}{aKT} \right) - 1 \right] \]  

(7)

The equation (7) shows the ideal PV cell characteristics and does not includes the practical I-V characteristics in a PV cell. The first term \( I_{PV \text{ Cell}} \) in equation (7) is proportional to the solar irradiance intensity while the second term is the cell current and voltage of the diode. Resistances are added in series and parallel to a circuit to form a practical PV cell. The elements with contact resistance of the PV cell are in series with the circuit while the leakage current of the circuit is represented using the parallel resistance. The accuracy of the equivalent circuit with single diode can be improved by adding large number of diodes to the circuit. (Atiq and Soori 2016, Saidi and Chellali 2017)

In a PV module along with the series and shunt resistance number of cells are connected either in series \( (N_s) \) or parallel \( (N_p) \) with the circuit.

\[ I = N_p I_{PV \text{ Cell}} - N_p I_{o \text{Cell}} \left[ \exp \left( \frac{q(V+IR_s)}{aKT} \right) - 1 \right] - \frac{V+IR_s}{R_p} \]  

(8)

The photon current incident on the solar cell mainly depends on the radiation from the sun and the temperature. This can be expressed as:

\[ I_{PV \text{ Cell}} = \left[ I_{PV \text{ Celln}} + KI(T-T_{ref}) \right] \frac{G}{G_n} \]  

(9)
The photon current is the light radiated current at standard conditions. The standard test condition values considered for a PV cell is 1000KW/m² irradiance and 25°C temperature. In equation (9) $I_{PVCelln}$ is the photon current at standard test condition, $K_I$ is the current temperature coefficient, $T_{ref}$ is the temperature at standard test condition, $G$ is the value of irradiance and $G_n$ is the irradiance value at standard test condition. (Saidi and Chellali 2017)

The diode current is a function of current and voltage and takes reverse saturation current at any temperature. Therefore, the reverse saturation current is given by. (Atiq and Soori 2016)

$$I_{ocelln} = \frac{I_{scn}}{\exp\left(\frac{V_{ocn}}{a\cdot V_{th}}\right)-1}$$  \hspace{1cm} (10)

$I_{ocelln}$ is the reverse saturation current at standard test condition. The temperature has an influence over the reverse saturation current and is given. (Atiq and Soori 2016)

$$I_{ocell} = I_{ocelln}\left(\frac{T}{T_{ref}}\right)^3 e^{\frac{q\cdot E_g}{a\cdot k}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)}$$  \hspace{1cm} (11)

The I-V and P-V characteristics are based on the irradiance and the temperature of the cell. The characteristics output changes based on the variations in solar radiance and the temperature. The design of a PV panel is done using these mathematical equations. (Anjali Rana 2015, Saidi and Chellali 2017)

![Graph](image_url)

Fig 3.5: I-V and P-V Characteristics of A Solar Cell. (Saidi and Chellali 2017)
3.2 Maximum Power Point Tracking

The Maximum Power Point Tracking system is an electronic device for tracking the maximum available energy resource thus, improving the output performance and efficiency of the solar PV panels. Due to variations in weather condition the output has a nonlinear behavior and changes frequently. This device helps to track the available power in the atmosphere and operate at maximum power point thus increasing the efficiency. In a PV panel the voltage at which maximum power is attained is called maximum power point. (Sharma and Jain 2014, Atiq and Soori 2016)

![Fig 3.6: I-V and P-V Power Characteristics Curve. (Sharma and Jain 2014)](image)

The MPP varies based on the solar irradiance and the temperature conditions. The characteristics of PV cell includes voltage source region and current source region. The solar cell will have high internal impedance at current source region while at voltage source region the solar cell will have low internal impedance. When the internal impedance matches the load impedances, maximum power will be transferred to load. MPP is located between the PV cells and the load to track the maximum power. While due to the variable climatic conditions the temperature and irradiance influence the panel efficiency therefore the MPP is designed to have fast response, reliable performance with less fluctuations. This control system cannot be connected directly to load due to balancing issues and thereby it is connected to a DC-DC converter. Converter delivers the maximum power from PV cell to load with proper management and matches the source and load.
impedances. The normally used are DC-DC step up or step-down converters. (Sharma and Jain 2014, Reddy and Rao 2015)

There are different types of MPPT techniques used and the most commonly used in PV generation are Incremental Conductance method, Perturb & Observe, Constant Voltage and Current Method, Fuzzy logic, Curve fitting method, open circuit voltage method, short circuit current method and so on. The most used techniques among these is the Perturb & Observe and the Incremental Conductance method. These techniques require less time for tracking and implementation is simple. (Sharma and Jain 2014, Reddy and Rao 2015)

3.2.1 Perturb and Observe

The Perturb and Observe is also known as hill climbing method. This method is commonly preferred because of the simplicity and applicability. In a PV module this system operates based on the variations in output power due to increase or decrease in the voltage. The system algorithm uses the PV curve of the solar panel. Here, the voltage of the PV panel is perturbed to change with voltage($dv$) and simultaneously change the output power($dp$). Both the variations must be along the same direction. If the operation of solar panel is away from the MPP point and the voltage is perturbed with slight change then there will be change in power which will be observed. If the operating point is moved towards the MPP the change in power will be positive and perturbation of voltage happen in same direction. If the operating point moves away from MPP the change in power will be negative resulting in perturbation of voltage in reverse direction. (Özçelik and Yılmaz 2015, Hamid, Rahimi et al. 2016)

The P&O method with oscillations around MPP tracks the maximum amount of power. The P&O MPPT algorithm is useful with the changes in the solar irradiance and the temperature conditions and these changes are resolved by decreasing the perturbation and slowing down the tracking. The P&O MPPT system woks according to the increase or decrease in the voltage of the panel and on comparison with the previous cycle PV output power value. (Özçelik and Yılmaz 2015)
3.2.2 Incremental conductance Method

The incremental conductance method is an alternative solution for the MPPT method. This is a differential method by deriving the PV power with respect to voltage. On differentiating the power with respect to voltage, the output must tend to zero and based on the positive or negative variations in change in power to change in voltage (dP/dV) the PV voltage gets increased or decreased. The incremental conductance method is stable to track the power at any changes in weather conditions. (Reddy, Narayana et al. 2018)

The algorithm of the incremental conductance method is differentiating the change in power to change in voltage.

\[
\frac{dP}{dV} = \frac{d(VI)}{dV} = \frac{IdV}{dV} + \frac{Vdl}{dV}
\]  \hspace{1cm} (1)

\[
I + \frac{Vdl}{dV} = 0
\]  \hspace{1cm} (2)

The \(\frac{dP}{dV}\) = 0 is at MPP

Therefore, \(-\frac{I}{V} = \frac{dl}{dV}\)  \hspace{1cm} (3)
In equation (3) the $-I/V$ is the instantaneous conductance and $dI/dV$ is the incremental conductance. On the base of operating point, a set of iterations are conducted using this derivation and these set of derivation will be zero at MPP. (Anurag, Bal et al. 2016)

$$\frac{-I}{V} = \frac{dI}{dV} \left( \frac{dP}{dV} = 0 \right)$$

$$\frac{-I}{V} < \frac{dI}{dV} \left( \frac{dP}{dV} > 0 \right)$$

$$\frac{-I}{V} > \frac{dI}{dV} \left( \frac{dP}{dV} < 0 \right)$$

The above three conditions are used to analyze the direction of perturbation in which the MPP is achieved. Normally a reference voltage is used for the operation of PV panel which is the $V_{MPP}$ and once the MPP is attained with maintaining the operation and the change in current ($\Delta I$) is made constant. Due to weather changes tracking algorithm interrupts the voltage reference to the new MPP which causes changes in the ($\Delta I$). (Anurag, Bal et al. 2016)

![Flowchart](image.png)

Fig 3.8: Incremental Conductance Method Flowchart. (Reddy, Narayana et al. 2018)

While selecting MPP for tracking the technique used must be efficient, accurate and economical for analyzing. The most commonly used MPP techniques for tracking are P&O and Incremental Conductance method. The reason is that they are simple in structure for implementation as well as requires very less tracking times. The techniques Perturb & Observe, and Incremental
Conductance method are more likely to be used where the parameter tuning is not necessary. These systems are of high cost for implementation and are used for large scale applications rather than small scale. The P&O method is used for where there is a variation in climatic conditions, mainly changing sun’s radiation and for quick changes in the environmental conditions. But, this method sometimes finalizes the changes from MPP rather than from radiation from sun therefore, the calculations go wrong. To eliminate this issue incremental conductance method takes place. This method is applicable in a digital environment and provides better results in a varying change in climatic conditions. This system attains lower oscillations within the maximum power point. The only drawback with this method is complex structure. Thus, these method are used mainly in large-scale purposes such as satellite applications. (Sharma and Jain 2014, Anurag, Bal et al. 2016)
CHAPTER 4

DC-DC CONVERTERS

A DC-DC converter is a power electronic device used to produce a regulated output by converting the voltage from one level to the other. The switched mode converters store the energy and converts this energy on a periodic basis and uses as the output at a different voltage level. This mode of converters is having higher efficiency in power conversion, since the switching frequency is higher there is minimal losses and due to storing of energy in the devices switching regulators can transform the voltages to be higher than the input or lower than the input. Different types of switching modes DC-DC converters used are boost converters, buck converters and buck-boost converters. These converter circuits include a power switch, diode, inductor and capacitor to transfer energy to output from the input. (Hart 2010, Nptel.ac.in 2018)

For an ideal switch, the input will be similar as the output when the switch is closed, and the output will be zero when switch is open. The open and close of a switch results in pulses and the output voltage over the time is given by

\[ V_O = \frac{1}{T} \int_0^T V_O(t)dt = \frac{1}{T} \int_0^{DT} V_S dt = V_S D \]  

(1)

D is the duty ratio which is the fraction of switching period when the switch is in closed condition. The output voltage is influenced by the duty ration for a dc component. When the switch is in
closed condition no voltage flows across it while, the switch is in open condition no current flows across it.

\[ D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} f \]  

(2)

Where D is the duty ratio, \( t_{on} \) is on period of switch, \( t_{off} \) is the off period of switch, \( f \) is the switching frequency. (Hart 2010)

4.1 Boost Converter

The boost converter is also termed as step up converter. In a DC-DC boost converter the output voltage will be higher than the input voltage. In a transformer the voltage is stepped up from low level voltage to high level which is same as the step up in converters. With the law of conversion of energy, the input power \( P_{in} \) must be equal to output power \( P_{out} \). Therefore, the output voltage from the boost converters will be higher than input voltage which results in a decrease in the output current whereas the input current will be higher. (Hart 2010, Ecetutorials.com 2018)

![Boost Converter Circuit](Nptel.ac.in 2018)

Fig 4.2: Boost Converter Circuit(Aptel.ac.in 2018)

When the switch is closed for a t period the inductor stores energy and inductor current rises while when the switch is open for t period the stored energy discharges towards the load through the diode. Here, the capacitance reduces the voltage ripple and diode prevents reverse current to flow from load to switch or source. (Ecetutorials.com 2018)
Here in fig 4.3 the switch in converter is closed for a period $0$-$T_{on}$ at this instant the inductor stores energy since the flow of current is through the inductor. When the switch is open the current flows parallel to the combination of capacitance and load. The energy stored in inductor is discharged and fed to load. Since high voltage appears in the circuit the change in current will be negative. The current decreases for an Off period. (Nptel.ac.in 2018)

The voltage across the inductor for a period of $0$ to $T$ is given by

$$V_L = L \frac{di}{dt}$$

On integrating the inductor voltage($V_L$) for the time $0$-$T$

$$\int_0^{T_s} V_L \, dt = 0 \quad (1)$$

$$\int_0^{T_{on}} V_d \, dt + \int_{T_{on}}^{T} (V_d - V_o) \, dt = 0 \quad (2)$$

$$V_d [t]_0^{T_{on}} + (V_d - V_o) [t]_{T_{on}}^{T_s} = 0$$

$$V_d T_{on} + V_d T_s - V_d T_{on} - V_o T_s + V_o T_{on} = 0$$

$$V_d T_s - V_o (T_s - T_{on}) = 0$$

$$V_d T_s - V_o (1 - D) T_s = 0$$
\[
\frac{V_o}{V_d} = \frac{1}{1-D}
\]

(3) (Hart 2010, Nptel.ac.in 2018)

In equation 2 the input voltage \( V_{\text{in}} = V_d \)

Switch On Period \( T_{\text{on}} = DT_s \) and Off period \( T_{\text{off}} = (1-D)T_s \)

\( T_{\text{on}} + T_{\text{off}} = T_s \)

In a boost converter as the duty ratio is increased, the denominator tends to be smaller thus giving a higher output voltage. If the duty ratio is equal to zero, the output voltage will be same as the input voltage. (Hart 2010, Nptel.ac.in 2018)

4.2 Buck Converter

Fig 4.5 Buck Converter Circuit (Nptel.ac.in 2018)
The buck converter is also termed as step down converter. In a DC-DC buck converter the output voltage will be lower than the input voltage. In a transformer the voltage is stepped down from high level voltage to low level which is same as the step down in converters. With the law of conversion of energy, the input power ($P_{in}$) must be equal to output power ($P_{out}$). Therefore, in buck converters the output voltage will be lower than the input voltage which leads to a higher output current than the input current. (Ectutorials.com 2018)

In a buck converter the inductor in the circuit withstand sudden variations in input current. When the switch is ON for a $t$ period the inductor stores energy and when the switch is open for $t$ period the stored energy discharges. Here, the dc current is supplied to load through the switch and the diode is in parallel with the load. (Hart 2010, Ectutorials.com 2018)

![Buck Converter Circuit in ON and OFF Period](Nptel.ac.in 2018)

When the switch $S$ is closed for a time $T_{on}$ the diode $D$ is reverse biased and is in off condition. The voltage at the load is same as the input voltage and the flow of current to the load is through the inductor. When the switch $S$ is open for duration of $T_{off}$ because of the negative inductor voltage the diode will be forward biased and the load voltage will be zero. The load current flows through diode when the switch is off. During off condition the continuity of load current is maintained therefore, transient voltages appearing across the switch is prevented. (Hart 2010, Nptel.ac.in 2018)
The inductor voltage $V_L$ for the time $0-T_s$

$$\int_0^{T_s} V_L \, dt = 0$$  \hspace{1cm} (1)

$$\int_0^{T_{on}} (V_d - V_o) \, dt + \int_{T_{on}}^{T_s} (-V_o) \, dt = 0$$  \hspace{1cm} (2)

$$(V_d - V_o)[t]_0^{T_{on}} + (-V_o)[t]_{T_{on}}^{T_s} = 0$$

$$(V_d - V_o)T_{on} = V_o(T_s - T_{on})$$

$$\frac{V_o}{V_d} = \frac{T_{on}}{T_s} = D = \text{duty ratio}$$  \hspace{1cm} (3)

$$V_o = DV_d$$  \hspace{1cm} (4)

![Fig 4.7 Graph Showing Waveforms of Buck Converter](Nptel.ac.in 2018)

For the buck converter $V_{in} = V_d$

Switch in $T_{on}$ $V_L = V_d - V_o$ and for switch in $T_{off}$ $V_L = -V_o$

In application of Buck converter, the output voltage is controlled by varied the duty ratio while the input voltage remains constant. (Hart 2010, Nptel.ac.in 2018)

**4.3 Buck-Boost Converter**

The Buck Boost converter is a DC-DC converter having the output voltage greater than or less than the input voltage. The output voltage magnitude is based on the duty cycle of the switch.
Buck-boost converters are called as step down or step up converters. There converters are same in function to a step down or step up transformer. According to the law of conservation of energy the input power($P_{in}$) should be same as the output power($P_{out}$). For buck-boost converter with step up mode the output voltage will be higher than the input voltage while the output current will be less than the input current. Likewise, in a step-down mode in buck boost converter the output voltage will be lower than the input voltage while the output current will be greater than the input current. (Hart 2010, Ecetutorials.com 2018)

![Buck-Boost Converter Circuit](Nptel.ac.in 2018)

Fig 4.8 Buck-Boost Converter Circuit(Nptel.ac.in 2018)

When the switch $S$ is in ON state, the diode is in reverse biased and the energy is stored in the inductor. The inductor current rises in the circuit and current flows through the inductor and switch. When the switch $S$ is in OFF state no energy is supplied from the input and the current starts flowing through the inductor, capacitor, diode and load. The inductor current falls and the stored inductor energy is transferred to load. Therefore, this converter is termed as indirect converter. The capacitor at the output terminal is large enough to supply a constant voltage at steady state condition. (Hart 2010, Ecetutorials.com 2018)

![Buck-Boost Converter in ON and OFF State of Switch](Nptel.ac.in 2018)

Fig 4.9 Buck-Boost Converter in ON and OFF State of Switch(Nptel.ac.in 2018)
In a steady state condition, the inductor voltage ($V_L$) on integrating over a period $0-T_s$ will be zero.

\[ \int_0^{T_s} V_L \, dt = 0 \]  
\[ \int_0^{T_{on}} V_d \, dt + \int_{T_{on}}^{T_s} (-V_o) \, dt = 0 \]  
\[ V_d T_{on} - V_o T_s + V_o T_{on} = 0 \]  
\[ V_d D T_s = V_o (1 - D) T_s \]  
\[ \frac{V_o}{V_d} = \frac{D}{1 - D} \]  
\[ V_o = V_d \frac{D}{1-D} \]  

Fig 4.10: Waveforms of Buck-Boost Converter in $T_{on}$ and $T_{off}$ (Nptel.ac.in 2018)

In equations the $V_{in}$ is same as $V_d$ and $D$ is the duty ratio.

When switch is ON $V_L = V_d$ and when switch is OFF $V_L = V_o$
The performance of buck-boost converter is depending upon the duty ratio. If the duty ratio is less than 50 percent it functions like a buck converter similarly if the duty ratio is greater than 50 percent then it acts like boost converter. Based on the duty ratio the output can be higher or lower than the input. Cascading these two converters gives buck-boost converter. (Hart 2010, Nptel.ac.in 2018)
CHAPTER 5

INVERTER

Inverters are power electronic devices used to transform a DC output to an AC output at a specified frequency. Inverters are classified based on the source voltage and source current. The main two classifications of inverters are voltage source inverter (VSI) and the current source inverter (CSI). For a voltage source inverter DC voltage supplied at the input of the inverter will have low impedances and for a current source inverter the supplied at the input of inverter current will be in variable with high impedances. The inverters are further classified based on the phases such as single-phase inverter and three-phase inverters. (www.tutorialspoint.com 2018)

5.1 Single Phase Inverter

Fig 5.1: Single Phase Sinusoidal Waveform(Australia 2018)

The single-phase inverters are of two types half bridge inverter and full bridge inverter which transforms the DC input to AC output at specified magnitude and frequency.
5.1.1 Half Bridge Inverter

The half bridge inverter forms a part of the full-bridge inverter with two switches and capacitors to each component by dividing the voltage to half. Therefore, the voltage across each capacitor is given by $\frac{V_{dc}}{2}$. In working of the half bridge inverter, the switch $S_1$ is closed the voltage across the load will be $(-\frac{V_{dc}}{2})$. When the switch $S_2$ is closed the voltage across the load will be $(+\frac{V_{dc}}{2})$. The output from the half-bridge inverter will be a bipolar pulse width modulated wave or a square wave. At times when the switch is in closed condition the voltage across the load be double that is $V_{dc}$. In the figure 5.2 shown below is half bridge inverter with $V_{dc}$ is the input voltage and $V_o$ is the output voltage.(Hart 2010, www.tutorialspoint.com 2018)

![Half Bridge Inverter Circuit](image1)

Fig 5.2: Half Bridge Inverter Circuit(Hart 2010)

5.1.2 Full Bridge Inverter

The full bridge inverter has four switches and the AC output is produced by closing and opening of the switches in a correct sequence. For a full bridge inverter two switches closes and opens simultaneously. The figure 5.3 shown below is of full bridge inverter with $V_{dc}$ input voltage and $V_o$ of output voltage.(www.tutorialspoint.com 2018)

![Full Bridge Inverter Circuit](image2)

Fig 5.3: Full Bridge Inverter Circuit(Hart 2010)
The working of the full bridge inverter, two switches $S_1$ and $S_2$ closes together for a cycle and $S_3$ and $S_4$ closes together for another. When the switches $S_1$ and $S_2$ closes the output voltage $V_o$ will be $(+V_{dc})$ while when the switches $S_3$ and $S_4$ closes the output voltage $V_o$ will be $(-V_{dc})$. Switches $(S_1, S_4)$ and $(S_3, S_2)$ these pairs will not close at the same time because short circuit happens in the DC source giving an output of zero.

### 5.2 Three Phase Inverter

The three-phase inverter circuit the output will be three phase AC from the DC input. The figure 5.4 shown below is the sinusoidal three phase output waveform. The switching action for a three-phase inverter occurs in every 60° angle interval. (www.tutorialspoint.com 2018)

![Three Phase Sinusoidal Waveform](image)

Every switch has a duty ratio of 50 percent. The switches $S_1$ and $S_4$ closes and opens in complementary to each other. Similarly, for the other pairs of switches also $(S_2$ and $S_5)$ and $(S_3$ and $S_6)$ they are complement to each other. Two types of conduction occur in the three-phase inverter 180° conduction mode and 120° conduction mode. (www.tutorialspoint.com 2018)
The figure 5.5 is the three-phase inverter circuit with six switches operating in T/6 cycle. The voltage will be $+V_{dc}$ or 0 through the $V_{A0}$, $V_{B0}$, $V_{C0}$ and the voltage across the line to line $V_{AB}$, $V_{BC}$, $V_{CA}$ will be $+V_{dc}$ or $-V_{dc}$ or 0. For the 180° conduction mode the switches are open for a 0-60° interval and output terminals are connected either in star or delta form. At the working three switches are closed ($S_1$, $S_5$, $S_6$) with terminal A and C to the positive point of source and B to the negative point of source. Likewise, five other continuous modes of operation take place for a three phase 180° conduction mode. (Hart 2010, www.tutorialspoint.com 2018)
The above figure 5.6 is the waveform representing the switching action at 180° modes of conduction in a three-phase inverter. The output obtained in the switching sequences are explained further.

When switches (S₅, S₆, S₁) closed, the voltage across $V_{an} = V_{cn} = V/3$ and $V_{bn} = -2V/3$

When switches (S₆, S₁, S₂) closed, the voltages across $V_{bn} = V_{cn} = V/3$ and $V_{an} = -2V/3$

When switches (S₁, S₂, S₃) closed, the voltages across $V_{an} = V_{bn} = V/3$ and $V_{cn} = -2V/3$

When switches (S₂, S₃, S₄) closed, the voltages across $V_{an} = V_{cn} = -V/3$ and $V_{bn} = 2V/3$

When switches (S₃, S₄, S₅) closed, the voltages across $V_{bn} = V_{cn} = -V/3$ and $V_{an} = 2V/3$

When switches (S₄, S₅, S₆) closed, the voltages across $V_{an} = V_{bn} = -V/3$ and $V_{cn} = 2V/3$. (Nptel.ac.in 2018)
CHAPTER 6

WIND ENERGY SYSTEM

Wind energy is one the most promising renewable source of energy to meet the growing demands of the world. It is environmental friendly and clean form of energy. The motion of air is termed as wind. The kinetic energy derived from the wind using wind turbines are converted to mechanical energy. This mechanical energy is further converted into electrical energy using generators. Different types of generators are available for wind energy generation and the most commonly used are permanent magnet synchronous generator(PMSG) and induction generators(IG). The field of excitation is provided by permanent magnets rather than excitation coils in permanent magnet synchronous generators. This is most commonly used in commercial purpose for electricity generation. These generators are termed as synchronous generators because the rotor speed always matches with the supply frequency. In high power applications permanent synchronous generators are mostly used because of low cost and maintenance, doesn’t require a dc supply for excitation and high efficiency.(Nath and Rana 2011, Anupam, Kulkarni et al. 2017)

Fig 6.1: Schematic Diagram of Wind Energy. (Schematic, 2019)
The figure 6.1 represents the schematic diagram for wind energy production. The wind turbine includes components such as rotor, blades, gearbox, nacelle, generator and tower. The main part of turbine is the nacelle consisting of the gearbox and generator. The rotor and nacelle are housed in the tower of the wind turbine. The wind falling over the rotor blades transfer kinetic energy to the rotor hub. The gearbox is used to increase the speed of the rotating shafts and the mechanical energy of the rotating shaft is converted to electrical energy by the generator. The output from the generator is fed to the inverter to produce AC output required at the grid for distribution. The figure 6.2 is the block diagram for a wind energy system.(Kumar, Ringenberg et al. 2016)

![Figure 6.2: Block Diagram of Wind Energy](image)

### 6.1 Wind Turbine Modelling

The aerodynamic power characteristics of a wind turbine depends on air density(\(\rho\)) kg/m\(^2\), coefficient of power(\(C_p\)), wind turbine swept area(\(A\)) m\(^2\) and wind speed(\(V\)) m/s. The coefficient of power is a function of tip speed ratio (\(\lambda\)) and blade pitch angle(\(\beta\)). The equation for power(\(P_w\)) can be written as

\[
P_w = 0.5 \rho AV^3 C_p (\beta, \lambda)
\]  

(1)

The tip speed ratio(\(\lambda\)) is defined as the ratio of rotational speed of wind turbine(\(w\)) and radius of wind turbine blade (\(R\)) to the wind velocity(\(V\)).

\[
\lambda = \frac{wr}{V}
\]  

(2)

On theoretical basis the maximum value of coefficient of power(\(C_p\)) is 0.59. the \(C_p\) is a fraction of upstream wind power and is captured by the wind turbine rotor blades while the remaining power is discharged to downstream. To achieve maximum torque for the wind turbines the blade pitch angle(\(\beta\)) is always kept to zero.(Naik, Reddy et al. 2014, Saidi and Chellali 2017)
6.2 Wind Turbine Generators

Wind energy is a renewable resource meeting the energy demands without depleting the fossil fuels and sustaining them for the future needs. The clean form of energy is abandonly available in nature. Wind energy conversion systems are based on the generators used in producing the electrical energy. There are two categories of wind speed turbines variable wind speed and fixed wind speed. The variable speed wind turbines are capable to attain maximum efficiency over wide range of wind speed while the fixed speed wind turbine gets its maximum efficiency at a constant wind speed. Due to high efficiency and reliability of the direct driven permanent magnet synchronous generator it is the most commonly used system for wind energy conversion.

6.2.1 Permanent Magnet Synchronous Generator

The permanent magnet synchronous generators convert the mechanical power produced by the wind turbine into electrical power. Later this power is fed to the grid or load through power electronic devices.

![Basic Diagram of a Wind Energy Conversion System](image)

In a PMSG two phases are used to derive dynamic model. The q-axis is 90° ahead of d-axis in direction of rotation. In a d-q reference frame rotating at synchronous speed the mathematical model is given by

\[
\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{ls}} (-R_s i_d + \omega_e (L_{qs} + L_{ls}) i_q + u_d)
\]  

\[
\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{ls}} (-R_s i_q - \omega_e [(L_{ds} + L_{ls})i_d + \psi_f] + u_d)
\]
The d and q refer to the d-q reference frame, \( R_s \) stator resistance, \( L_d \) and \( L_q \) are the d and q axis generator inductances, \( L_{ld} \) and \( L_{lq} \) are the d and q axis leakage inductance of generator, \( \psi_f \) are the permanent magnetic flux and \( \omega_e \) are the electrical rotating speed of the generator.

The torque equation for a PMSG

\[
\tau_e = 1.5p \left( (L_{ds} - L_{ls})i_d i_q + i_q \psi_f \right) \tag{3}
\]

\( p \) is the number of poles in a generator. (Naik, Reddy et al. 2014)

### 6.2.2 Induction generator

The most complicated part in wind energy generation system includes the generator. The induction generator requires excitation capacitor to self-excite in before generating power. The IG are applicable for low power wind turbines because of low cost, robustness and no cogging torque. IGs requires a gearbox for small wind turbine applications since it rotate so rapidly. IGs include electromagnetic state variables, stator, rotor and electromagnetic transients. The rotor slip ratio is given by

\[
s = \frac{\omega_s - \omega_g}{\omega_s} \tag{1}
\]

The electrical torque and generator power is given by

\[
T_e = \psi_{qr} I_{dr} - \psi_{dr} I_{qr} \tag{2}
\]

\[
P = V_{ds} I_{ds} + V_{qs} I_{qs} \tag{3}
\]

With change in time the stator and rotor inductances changes and therefor the complexity in the model is overcome by using Park’s Transformation method. The slip output will be positive in the monitoring mode and negative in the generating mode. \( \Psi \) in equation 2 represents the magnetic flux. In the equation (3) \( V_{ds} \) and \( V_{qs} \) are the stator direct and quadrature axis voltage in the induction generator of a wind turbine. The \( I_{ds} \) and \( I_{qs} \) are the stator direct and quadrature axis current of the induction generator respectively. (Sarkar, Julai et al. 2006, Kabalci 2013)
CHAPTER 7

HYBRID ENERGY SYSTEM

Hybrid power generation systems are the best possible solution to meet the increasing demands of the future. Hybrid energy systems mean combination of two or more energy sources to generate electricity. Renewable energy sources depend on the weather conditions. When the sun’s radiation is higher normally the temperature will be high which is enough for generating solar energy but during this time the wind energy will be feeble. Similarly, during the times of wind the atmospheric condition will be cloudy with chances of rain and the visibility will be dark with very less sunlight. Therefore, depending on a single source of energy is not worth for a continuous power generation. The energy from sun is available during the day time while wind is available during day and night. However, the intensity of wind is higher during the night time in effect one or the other power supply will be available throughout. As per seasonal variations the energy from sun is more useful during summer seasons and energy from wind is beneficial during the times of winter since the weather will be windier. Therefore, the integration of renewable energy sources provides better performance and reliable output than standalone systems during any cycle of the power generation system. (Gowtham and Royrichard 2014)

The hybrid energy systems aim to combine solar and wind energy connected to grid with controlling techniques for maximum power generation. The benefit of power generation unit coupled to grid is that, at times of any shutdown occur in the production from the solar or wind energy the grid can act like a source or a backup system. The excess energy generation from the renewable resources is stored in the grid and is supplied to meet the load demand. The hybrid power generation is a best solution in coming future because the seasonal variations for the sun and wind can be solved on combining the energy and output performance is improved. (Gowtham and Royrichard 2014)
Fig 7.1 Schematic Diagram of Hybrid Solar-Wind Energy

The figure 7.1 represents the diagram for a hybrid power generation using solar and the wind energy. The two energy resources are combined through controlling techniques before powering the grid or the load. The solar energy from the sun with the help of MPPT technique is fed to converter to produce a regulated DC output and this output is fed to inverter to form AC output. The mechanical energy produced by the wind turbine is converted to electrical energy using generator and is fed to inverter. Both the output are combined and supplied to the AC grid. Due to seasonal variations of sun and wind, and for continuous power generation, a hybrid system plays a significant role by combining solar and wind energy. (Shen, Izadian et al. 2014)

Fig 7.2: Block Diagram of Hybrid Energy System
The above figure 7.2 is the block diagram for a hybrid energy generation system using the solar and wind power. The figure gives an overall idea of the hybrid system. The energy from sun is captured and transformed for generating power for that tracking technique is used to utilize the maximum available power from energy resource. The tracking Method used is Perturb and Observe(P&O). The utilized power is sent through a boost converter to step up the solar DC output power to supply to the inverter. Inverter converts the DC power to AC power. A three-phase inverter is used to transform the input to AC to supply to the grid to meet the energy needs. Likewise, the energy from wind is transformed to useful form with a wind turbine capturing the rotating wind speed and converting to mechanical energy. The energy from wind is transformed to electrical energy with generator. The generator used is permanent magnet synchronous generator. The generated power is sent to the grid to meet the needs.
CHAPTER 8

METHODOLOGY

The research project was done using the Matlab/Simulink software. Using the Matlab/Simulink blocks in the Simulink library the hybrid PV-wind model was designed. Mathematical equations are used and analyzed for the design of the hybrid power generation system. Matlab stands for Matrix Laboratory and was developed by MathWorks and it is a high-level programming language which can interact with the environmental numerical calculations, visuals and the programming. It also helps to create models using the physical blocks in the inbuilt Matlab/Simulink library, does matrix calculations and the programs written in other computer languages can be interfaced in Matlab to analyze the data. Matlab programming is widely used in the field of science and engineering. It also has a wide library of mathematical functions for linear algebra, statics, Fourier analysis, integration and differentiation of numerical equations.

The methodology adopted for the design of a hybrid power generation system using solar and wind power is connected to a grid system for the transfer of power to meet the demands. The hybrid system is combined use of solar energy and wind energy from available resources with efficient and maximum utilization along with power-control. Based on the climatic conditions and availability of solar and wind power this system allows to supply power to load and the grid. The energy from solar is available and is tracked with MPPT technique such as Perturb and Observe method. According to the available voltage of the solar cells and the temperature the output solar energy is produced. The energy from solar is boosted with the help of DC-DC boost converters to supply to a DC-AC inverter circuit to supply to the load. For a wind energy system, the speed of rotor of the wind turbines are captured by permanent magnet synchronous machines and the output wind energy is coupled with the turbines to convert to electrical energy. The output is fed to inverters for conversion of DC to AC to supply to load.

The system works at normal standard temperature and radiation from sun and the normal wind speed availability. Combining these techniques such as converters, inverters, transformers, controlling techniques like PI, PWM for internal operations it can develop a hybrid system. This hybrid system is developed and modelled in Matlab/Simulink software with the help of Matlab block sets.
8.1 Renewable Energy in Kerala

Fig 8.1: Map Showing the Parts of Kerala

For developing a hybrid power generation system using renewable energy the first and most required data is the availability of the renewable energy resources over an area. For solar energy, the irradiance and maximum sunshine hours must be known along the temperature. Sun’s radiation and temperature are the main factors influencing the generation of solar energy. While for wind energy, the wind speed and the topographical changes effecting the wind speed needs to be known. A detailed analysis of solar radiation and wind speed is required to calculate an average monthly output of energy the area can produce.

The data from Kerala is shown as a reference to prove that the place is feasible for an installation of hybrid power generation unit using sun and wind energy. Kerala has a high accessibility to sun and wind energy, combining these two resources will give maximum output for power generation.

8.2 Solar Energy in Kerala

The parts of Kerala have wide solar energy availability and by the March 2017 the installed capacity of solar power was 75.42MW. The studies show that the daily sunshine hours on an average in the parts of Kerala is about (7-9) hours daily with an average annual solar irradiance of
about 5.68kWh/m²/day with average daily temperature of 28°C. The month of March, April, May is the hottest, having an average temperature of 29°C and a sunshine of 8 hours daily. While the month of March is the hottest with an average solar irradiance of 6.68kWh/m²/day. (Holiday-weather.com 2018)

The above figure 8.2 represents the average monthly temperature range in the parts of Kerala. From the figure it is clear the highest temperature is in the month of March, April and May with 29°C which is the hottest. The month of January and February are having average temperature with 28°C very close to the highest month temperature. The remaining months are having temperatures with the range of 27°C close to the highest range and these months are warm but not hot. (Holiday-weather.com 2018)

The below figure 8.3 shows the average monthly solar irradiance in Kerala. The month of March have the highest exposure to sun’s radiation with average irradiance of 6.68kWh/m²/day. This is followed by the month of February and April with an average radiance of 6.51kWh/m²/day and 6.37kWh/m²/day. The least irradiance is in the month of July with an average of 4.74kWh/m²/day. The remaining months are having irradiance level within the range of 5kWh/m²/day on an average which is sufficient enough for energy generation from solar. (Engineers 2018)
Fig 8.3: Average Monthly Solar Irradiance in Kerala (Engineers 2018)

Fig 8.4: Average Daily Sunshine Hours in Kerala (Holiday-weather.com 2018)
The above figure 8.4 represents the daily sunshine hours in Kerala. The month of January and February have the maximum hours of sunshine with 9 hours daily. This is followed by the months of March, April, May with daily sunshine of 8 hours. The least sunshine hours are in the months of June and July with daily sunshine of 5 hours. On an average at least (6-7) hours of sunshine is available daily in every month.(Holiday-weather.com 2018)

8.3 Wind Energy in Kerala

The wind speed is mainly based on the topography and the various climatic factors. The wind speed and direction changes rapidly rather than on hourly basis. The daily wind speed on an average in the parts of Kerala is about 12.9mph and varies with climatic conditions.

![Fig 8.5: Average Hourly Wind Speed(Weatherspark.com 2018)](image)

The above figure 8.5 represents the average hourly wind speed in Kerala. From the diagram it is clear the highest wind speed is available during the month of June with an average hourly wind speed of 12.9mph. the wind speed is manly based on the location topography and climatic condition. The speed and direction of wind changes hourly. From the figure it shows, the most
Available wind speed is during the months starting from May to October with an average hourly wind speed of 9.5mph. The least available wind speed is during the month of March with 6mph and from October to May the wind speed available hourly is within the range of (6-8.5) mph on an average. (Weatherspark.com 2018)

![Wind Direction in Percentage of Hours](Weatherspark.com 2018)

Fig 8.6: Wind Direction in Percentage of Hours (Weatherspark.com 2018)

The above figure 8.6 shows the wind direction percentage in Kerala. From the month of March to November wind flows from the west direction. The maximum percentage of wind flowing from west direction is available during the month of June with a highest percentage of 99%. From the month of November to March the flow of wind is from east direction and the maximum percentage of wind flowing from east direction is available during the month of January with a peak percentage of 78%. (Weatherspark.com 2018)
CHAPTER 9

EXPERIMENTAL SETUP

The PV and Wind energy systems are modeled in Matlab/Simulink software using the Simulink blocks. To start with a Simulink model first the Matlab/Simulink software is started. Open a new Simulink file and the file is saved. Using the block sets from library, these blocks are added to the file, then blocks are connected, initiate the blocks by adding values and thereby model is created. Further updates in the model is done, initiated the model. Then the model is simulated. The simulation output is viewed.

9.1 PV Simulink Model

![Fig 9.1: PV Simulink Model](image)

The above figure 9.1 is the PV Matlab model. The model is created based on the basic equivalent circuit diagram for a solar cell. In this model an extra diode is added to the equivalent circuit to improve the accuracy of the I-V characteristics. The diode is attached in parallel with the first diode in the circuit. As discussed earlier the model is designed using the theoretical equivalent circuit equations. Comparing with the single diode model the accuracy with two diode models is
better. Using a two-diode model makes the circuit more complex in work therefore a single diode model is preferred due to its simple performance. Therefore, the basic equation for a two-diode circuit is given by

\[ I = I_{PV} - I_{D1} - I_{D2} \]  \hspace{1cm} (1)

\[ I_{D1} = I_{O1} \times \left[ \exp \left( \frac{V}{A_{1} \cdot V_T} \right) - 1 \right] \]  \hspace{1cm} (2)

\[ I_{D2} = I_{O2} \times \left[ \exp \left( \frac{V}{A_{2} \cdot V_T} \right) - 1 \right] \]  \hspace{1cm} (3)

Substituting the equations 2 and 3 in equation 1 along with addition of series and shunt resistance to the circuit gives an overall equation of

\[ I = I_{PV} - I_{O1} \times \left[ \exp \left( \frac{V}{A_{1} \cdot V_T} \right) - 1 \right] - I_{O2} \times \left[ \exp \left( \frac{V}{A_{2} \cdot V_T} \right) - 1 \right] - \frac{V + R_s \cdot I}{R_{SH}} \]  \hspace{1cm} (4)

In equation 4 \( I_{O1} \) is the reverse saturation current by diffusion and \( I_{O2} \) is the reverse saturation current due to recombination. \( A_1 \) is the diode reality factor of diode 1 and \( A_2 \) is the diode reality factor diode 2. (Bonkoungou, Koalaga et al. 2013)

The light incident on the PV as photon current which is influenced by the temperature and solar irradiance is given by

\[ I_{PV} = (I_{PV,n} + K_i \cdot \Delta T) \times \frac{G}{G_n} \]  \hspace{1cm} (5)

\( I_{PV,n} \) is the light incident on solar panel under standard test conditions (STC)

The diode reverse saturation current equation is given by

\[ I_0 = I_{O,n} \times \left[ \frac{T_n}{T} \right]^3 \times \exp \left[ \frac{qE_g \cdot \left( \frac{1}{T_n} - \frac{1}{T} \right)}{AK} \right] \]  \hspace{1cm} (6)

The improved nominal saturation current equation for a single diode model is given by

\[ I_{O,n} = \frac{I_{sc,n} + K_i \cdot \Delta T}{\exp \left( \frac{V_{oc,n} + K_v \cdot \Delta T}{A \cdot V_{T,n}} \right) - 1} \]  \hspace{1cm} (7)

\( K_i \) and \( K_v \) represents the short circuit temperature coefficient and \( I_{sc,n} \) is the short circuit current, \( V_{oc,n} \) is the open circuit voltage, \( G_n \) is the irradiance, \( T_n \) all these parameters under standard test
conditions. Based on the above equations the PV design is modelled in the Matlab software. (Bonkoungou, Koalaga et al. 2013)

The input to the PV model is the solar irradiance and the temperature based on these two factors output current voltage and power is generated. The solar irradiance and temperature have much influence over the output and varies upon these input changes. The produced output current and voltage is supplied to the converter circuit. The output from the solar panels are in the form of DC power which is supplied to a converter to produce a regulated DC output.

9.2 Maximum Power Point Tracking

The above figure 9.2 represents the Simulink model for MPPT using P&O method. For the design of maximum power point tracking technique Perturb and Observe (P&O) is used with PV systems giving the output pulses to the converter. Tracking techniques are used to track the maximum available energy from the resource. The system functions based on the operating point moving towards the maximum power point. The system current and voltage sensors to measure the output from the solar panel.
The P&O method evaluates the previous cycle of input power. This method performs well under steady change in the irradiation values. As the operating point is moving towards MPP the voltage is increased with increment in power and if the operating point is moving away from MPP the voltage is decreased with decrement in power. If the value of power is incremented the perturbation happens to be in same direction whereas, the next perturbation will be in opposite direction on decrement in power. The iteration of change in voltage and change in power continues and a PI controller is added to modify the model and to test under various solar irradiance. The cycle continues until MPP is attained. (Ram, Rajasekar et al. 2017)

The MPPT output is supplied to the input of the switch of the boost converter. The entire mechanism is based on the power from the PV panel. The inputs are current (I\textsubscript{PV}) and voltage (V\textsubscript{PV}) are supplied and then by differentiating these input we get dI and dV. These are coupled together to form the output power to supply to PI controller. The PI controller generates the signals for generation of PWM signal for the boost converter switch. As the magnitude of PI signal changes, the dimensions of the PWM pulses also changes. This changes the ON/OFF duration in the converter. The changes happening in the MPPT is proportional to changes in the converter. The reference signal to send to the PI has variations the output also varies then the PWM signal changes. Thus, the duration of ON/OFF in the switch changes the power converter ratio will also change. The MPPT system is used to track the maximum energy and to eliminate the abnormal changes within the PV panel and to generate the required PWM pulses for the converter switch.

9.3 Boost Converter

The below figure 9.3 represents the high step up boost converter circuit diagram in Matlab/Simulink. The output from the solar panels is in the form of DC power and is fed to a DC-DC converter. The output from the panels are either stepped up or stepped down to a regulated DC output with help of converters. Here in this model a Step-up converter is used. Boost converter converts the input DC voltage to high output DC voltage. The converters function based on the switching frequency and the duty cycle to produce a controlled DC output. The MPPT output pulses are sent to the input of the converter switch.
Fig 9.3: Simulink Model of Boost Converter

In the figure the PWM pulses sent from the MPPT is sent to the converter switch $T_1$. Two switches function in the circuit to give a controlled DC output to send to the inverter. The converter functions based on the switching cycle. The output DC error signal and constant DC is fed to the feedback loop. With help of PI controller signals are produced and on comparing with the repeating triangular signal the PWM pulses are generated and are sent to the switch $T_1$. This process is done to avoid any fluctuations in the DC-DC converter circuit.

9.4 Inverter Circuit

Fig 9.4: Simulink Model of Inverter
The above figure 9.4 is the model of an inverter circuit in Matlab/Simulink. The output from the high step up boost converter is fed to the input of the inverter. Inverter circuit is used to convert the DC to AC to supply to the grid. In this model a universal bridge is used as the inverter switch to convert the dc power to ac and is fed through a three-phase series RLC branch and output is given. The output produced will be a sinusoidal three phase graph.

9.5 Wind Energy Simulink Model

![Simulink Model of Wind Energy System](image)

Fig 9.5: Simulink Model of Wind Energy System

The above figure 9.5 is the Simulink model of a wind energy system. The wind turbine model as three inputs to the system generator speed, pitch angle and wind speed. The output from the wind turbine model is torque which is supplied to the generator shaft. The permanent magnet synchronous generator(PMSG) converts the mechanical energy produced by the wind turbine into electrical energy. The electrical output from the generator is supplied to the grid or the load through the three phase V-I measurement block. The measurement block is always placed at output side to process the current and voltage sent from the generator. The synchronous generator is of 60kVA rating with 400V and 50Hz frequency. The input wind speed to the model is 12m/s, the blade pitch angle in degrees and the value is zero, the generator speed input in per units of the base rotational speed is 1.2. The model is designed to have a total output of 1.5MW therefore, 25 wind
energy model having capacity rating of 60KW is combined. Then the combined output is supplied to grid through the measurement block.

9.6 Hybrid PV-Wind Energy Simulink Model

Fig 9.6: Simulink Model of Hybrid PV-Wind Energy System

The figure 9.6 is the Hybrid PV-Wind energy system modelled in Matlab/Simulink. The combination of two renewable inputs solar energy and wind energy forms the hybrid model.

The data from Kerala is shown as a reference to prove that the place is feasible for an installation of hybrid power generation unit using sun and wind energy. Kerala has a high accessibility to sun and wind energy, combining these two resources will give maximum output for power generation. The hybrid model using solar and wind is developed modifying and improvising the base models. Further to trial and error method the hybrid system is simulated (Bogaraj and Kanakaraj 2012, Anjali Rana 2015, Atiq and Soori 2016)

The bottom part of the figure represents the solar energy system with a solar PV module producing \( I_{PV} \) and \( V_{PV} \) and with the MPPT technique maximum energy tracked and send to the DC-DC converter switching pulses. The output from solar module is sent to the high step up boost converter to produce a controlled DC output. The DC power is fed to inverter circuit to produce
AC power. Then through the three phase V-I measurement the produced sinusoidal AC output is sent to the grid and the electrical loads.

The middle portion of the figure represents the wind energy system. Wind turbines converting the kinetic energy to mechanical energy with help of generator and is supplied through a three phase V-I measurement block. The output from the wind power system will be sinusoidal AC output sent to the grid and to the electrical loads.

To have a control over the grid side converters for PV and wind, a constant voltage link is maintained. The main aim is to maintain a DC link voltage constant by the grid side converters. To find a solution to this a voltage-based vector control method is suggested. Mathematical modelling methods are used for the control strategies and the PWM converter is based on current regulated having the direct axis current to regulate the DC link voltage and the quadrature axis current for the reactive power. the transfer of three phase quantities to two phases is done using the d-q theory. The control scheme utilizes the current control loop. The $i_d$ and $i_q$ where $i_d$ from the dc-link voltage error through the PI controller. For the control design there are two loops such as the inner current loop and outer voltage loop. The line resistance and reactance for the current loop and dc capacitor for the voltage loop.(Krishnaveni, Balachandar et al.)

The Hybrid PV-Wind energy system is a grid connected model. The grid is a source whereby acting as a backup system for the renewable energy in case of any power shutdown. The grid also acts as a storage system at times of excess energy generation by the renewable energy systems. In case, if there is shortage of power from solar or wind or these sources are not able to meet the load demands the grid will automatically cover the entire demand.
CHAPTER 10

RESULT AND ANALYSIS

10.1 Simulation Results of PV Module

Fig 10.1: P-V Curve of the PV Module

Fig 10.2: I-V Curve of PV Module

65
The above two figures 10.1 and 10.2 represents the P-V and I-V characteristics for a PV module at standard test conditions of temperature 25°C and solar irradiance of 1000W/m². In the figure 10.1 the x-axis indicates the voltage values in volts and y-axis indicates the power values in watts. While in figure 10.2 the x-axis indicates the voltage values in volts and y-axis indicates the current values in amperes. From the figure the short circuit current $I_{sc}$ is 74A and open circuit voltage $V_{oc}$ is 360V and the maximum power obtained is 20KW.

Observations were done on varying the solar irradiance values. The irradiance values are varied from 250W/m² to 1000W/m² at a temperature of 25°C. On varying the irradiance value keeping the temperature constant it is observed that the current increases. The solar irradiance has influence on the current value. The effect of solar irradiance on voltage is very minimal. As the irradiance value is increasing the power also increases. Power is increased because of the increment in current value.

Observations are done on varying the temperature value. The temperature values are varied from 25°C to 100°C keeping the irradiance value at 1000W/m². On varying the temperature value keeping the irradiance same it is observed that the value of voltage decreases, and the current value remains somewhat same. Temperature variation has much more effect on voltage. As the temperature value increases the power value decreases. Power is decreased because of the decrement in the voltage value.

**10.2 Simulation Result of Inverter Output of PV**

The figure below 10.3 is the simulation output for an inverter circuit. The PV module input in DC form is stepped up in boost converter and fed to inverter to form an AC output. The graph is of two parts with upper portion representing the AC voltage in volts and bottom portion representing the AC current in amperes. The x-axis indicates the time while y-axis represents the voltage and current. The converter DC power of a PV panel to AC power by the inverter circuit is shown in the graph.
Fig 10.3: Simulation results of Inverter Output of PV

10.3 Simulation Result of Wind Energy Systems

Fig 10.4: Output Voltage of Wind Power System
Fig 10.5: Output Current of Wind Power System

The figure 10.4 and 10.5 represents the output waveforms of wind power systems. The figure 10.4 is the output graph of voltage and the figure 10.5 is the output graph of current. The x-axis indicates the time and the y-axis is the voltage and current.

10.4 Simulation Result of Hybrid Energy System

Fig 10.6 Output of Hybrid Energy System
The above figure 10.6 represents the output from the combined solar and wind energy system. The output for the hybrid system will be the combined solar energy plus the wind energy. The output from the hybrid model first two graphs is the output of $V_{\text{rms}}$ and $I_{\text{rms}}$ which is the DC equivalent output waveforms. The middle two graphs represent the real power and reactive power of the power distribution of the hybrid energy system. The bottom graphs represent the sinusoidal voltage and current output from the hybrid energy system. From the hybrid system supply is fed to the load also and power remaining is supplied to the grid.

On combining the hybrid system using the solar and the wind energy to power the grid. The generated power from wind is connected parallel and shared with PV system. There is a difference in generation from wind and solar because sources depend on varying climatic conditions therefore, there is likely to be inequality in the measurement of power even though the two systems are connected in parallel to the grid.
CHAPTER 11

CONCLUSION

The thesis aims to focus on the study of a hybrid PV-Wind power generation system for a grid connected application using the Matlab/Simulink software. Estimation of the solar irradiance and wind speed data in the parts of Kerala was done as a reference to prove the feasibility and with the availability of energy it is possible to propose and develop a model. The parts of Kerala have an average solar irradiance of 5.68kWh/m²/day with an average temperature of 28°C. Annually Kerala is well exposed to sun’s radiation which is approximately 7 hours of sunshine a day. In case of wind, study shows that the parts of Kerala have a good resource of wind energy with an average wind speed of 12.9mph. Wind speed direction and topography influence much on the wind speed.

Generation of power from single source of renewable energy cannot meet the load demands therefore, hybrid PV-Wind model is proposed to compensate the effects of environmental factors and climatic variations of the resources affecting the continuous operation of power generation. For efficient tracking of solar energy Perturb and Observe (P&O) MPPT technique is used and a boost converter is used to eliminate fluctuations at the Inverter to convert to AC power. Wind energy system with permanent magnet synchronous generator produces sinusoidal AC power. the two energy sources are combined to power the grid to meet the demands.

The hybrid model was modeled in Matlab/Simulink software and output is verified. The results show that solar radiation and temperature influences the output of the system. As the solar irradiance increases the value of current increases simultaneously the output power increases while increase in temperature decreases the value of voltage which affects the decrement in power. the wind speed and direction of wind are main factors affecting the output and results show that sinusoidal AC power is obtained with slight variations due to the fluctuations in wind speed. Overall, the hybrid system gives an approximate output of 1.5MW. Combining these two renewable sources for generation of electricity to meet the demands gives a clean energy output.
CHAPTER 12

FUTURE SCOPE OF THE PROJECT

The project is efficient for a continuous power generation, but power quality issues effects the performance of the overall systems. Power quality issues includes voltage sag, voltage swell, harmonics, transients which is mainly reduce the quality of power generation from the solar and wind energy. The usage of more power electronic devices also has an impact of the energy output leading to fluctuations. To overcome the power quality issues, it is recommended to use some techniques like implementing static compensators, series type LC filters UPQC. DSTATCOM helps to eliminate the harmonics, power factor correction and balance the load. For stability purpose STATCOM is used. Advanced methods need to be used to record the solar and wind data so that an estimation of power can be calculated for a continuous energy supply. Different MPPT techniques are available for tracking of the resources. (Aggarwal and Nijhawan 2016)
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APPENDICES

A. Average monthly data of Solar Irradiance, Temperature, Sunshine Hours in Kerala

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Irradiance kWh/m²/day</th>
<th>Average Temperature °C</th>
<th>Sunshine Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>5.98</td>
<td>28</td>
<td>9</td>
</tr>
<tr>
<td>February</td>
<td>6.51</td>
<td>28</td>
<td>9</td>
</tr>
<tr>
<td>March</td>
<td>6.68</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>April</td>
<td>6.37</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>May</td>
<td>5.90</td>
<td>29</td>
<td>7</td>
</tr>
<tr>
<td>June</td>
<td>4.89</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>July</td>
<td>4.74</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>August</td>
<td>5.34</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>September</td>
<td>5.67</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>October</td>
<td>5.15</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>November</td>
<td>5.39</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>December</td>
<td>5.55</td>
<td>27</td>
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</tr>
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</table>

B. Average hourly data of Wind speed, Wind direction in Kerala

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<thead>
<tr>
<th>Month</th>
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<td>8.55</td>
<td>From East with 79%</td>
</tr>
<tr>
<td>February</td>
<td>6.7</td>
<td>From East with 67%</td>
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<tr>
<td>March</td>
<td>6.3</td>
<td>Changes from east to west</td>
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<tr>
<td>April</td>
<td>7.55</td>
<td>From West with 84%</td>
</tr>
<tr>
<td>May</td>
<td>10.35</td>
<td>From West with 98%</td>
</tr>
<tr>
<td>June</td>
<td>12.55</td>
<td>From West with 99%</td>
</tr>
<tr>
<td>July</td>
<td>12.65</td>
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<td>August</td>
<td>12.15</td>
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<td>October</td>
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C. PV specifications

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D. PMSG Specifications

The generator specifications for the wind generator
E. The Simulink model of a PI controller circuit

F. The Simulink model of a Grid
G. Output P-V, I-V Characteristics Observations from the Matlab/Simulink Model

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Solar Irradiance W/m²</th>
<th>Voltage V</th>
<th>Current A</th>
<th>Power W</th>
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</thead>
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