(SOLAR CELL ARRAY MODELING AND ITS GRID INTEGRATION)

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Abstract : The photovoltaic energy as one type of renewable energy has attracted in the past decade a great interest due to its free availability, to its ease of use relatively to other electricity resources, and its "green" operation on the entire earth planet. So it is necessary to highlight its operation, its use, its evolution, its advantages, and furthermore its capability to solve several problems on the electric grid. The advances in this field of electrical engineering are great till now and keep discovering new contributions which are illuminating the future plan of this industry. On the other hand, the photovoltaic energy as an additional source on the grid requires studying its behavior under specific circumstances like electric faults, islanding operation, and so on. Solar energy, radiant light and heat from the sun, has been reined by humans since ancient times using a range of ever-evolving technologies. Solar radiant energy accounts for most of the usable renewable energy on earth. Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. In this thesis, the PV array is modeled and its voltage-current characteristics and power-voltage characteristics are simulated and optimized. The main encumbrance for the reach of Photovoltaic systems is their low efficiency and high capital cost.

Governments around the world are facing a steadily rising demand on global electric power. To face this challenge, they are striving to put in place regulatory guidelines to aid the adoption of best practices by utilities in terms of the Smart Grid and renewable energy applications. Smart Grid organization provides the consumers with the ability to monitor and control energy consumption. This is crucial because as the world population grows the electricity demand will also increase, but at the same time, we will need to reduce our electricity consumption to fight global warming.

By using the Smart Grid, energy consumers will have an incentive to create power on their own with the use of wind turbines or solar paneling, and subsequently sell any power that is generated in excess to electrical companies. Several researches are being made to improve the system and reduce its cost and size. As a result, the photovoltaic (PV) system is becoming much easier to install but the efficiency of solar module is still low (about 18%). Furthermore, it is desirable to operate the module at the peak power point.

In this thesis, the above ideas are studied, simulated in Matlab/Simulink, and the results are analyzed to end up with a conclusion. They are described with explanatory schematics and their results are exhibited using Matlab model screenshots to demonstrate the concept. In the end of this thesis, a future work plan is presented to implement more advances in this field of electrical engineering.

Introduction

1.1 Background and Overall Trends

Governments around the world are facing a steadily rising demand on global electric power. To face this challenge, they are striving to put in place regulatory guidelines to aid the adoption of best practices by utilities in terms of the Smart Grid and renewable energy applications. Smart Grid organization provides the consumers with the ability to monitor and control energy consumption. This is crucial because as the world population grows the electricity demand will also increase, but at the same time, we will need to reduce our electricity consumption to fight global warming.

By using the Smart Grid, energy consumers will have an incentive to create power on their own with the use of wind turbines or solar paneling, and subsequently sell any power that is generated in excess to electrical companies. Several researches are being made to improve the system and reduce its cost and size. As a result, the photovoltaic (PV) system is becoming much easier to install but the efficiency of solar module is still low (about 13%). Furthermore, it is desirable to operate the module at the peak power point.

This thesis will discuss about the photovoltaic system, the power electronics interface and the method to track the maximum power point (MPPT) of the solar panel.

1.2 The need for Renewable Energy

Renewable energy — wind, solar, geothermal, hydroelectric and biomass provides substantial benefits for our climate, our health, and our economy. Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike dwindling conventional fossil fuels. The global energy crunch has provided a renewed impetus to the growth and development of Clean and Renewable Energy sources. Clean Development Mechanisms (CDMs) are being adopted by organizations all across the globe. Apart from the rapidly decreasing reserves of fossil fuels in the world, another major factor working against fossil fuels is the pollution associated with their combustion. Contrastingly, renewable energy sources are known to be much cleaner and produce energy without the harmful effects of pollution unlike their conventional counterparts. Generating electricity from renewable energy rather than fossil fuels offers significant public health benefits. The air and water pollution emitted by coal and natural gas plants is linked to breathing problems, neurological damage, heart attacks, and cancer. Replacing fossil fuels with renewable energy has been found to reduce premature mortality and lost workdays, and it reduces overall healthcare costs . The aggregate national economic impact associated with these health impacts of fossil fuels is between $361.7 and $886.5 billion, or between 2.5 percent and 6 percent of gross domestic product (GDP).

Wind, solar, and hydroelectric systems generate electricity with no associated air pollution emissions. while geothermal and biomass energy systems emit some air pollutants, total air emissions are generally much lower than those of coal- and natural gas-fired power plants.

In addition, wind and solar energy require essentially no water to operate and thus do not pollute water resources or strain supply by competing with agriculture, drinking water systems, or other important water needs. In contrast, fossil fuels can have a significant impact on water resources. For example, both coal mining and natural gas drilling can pollute sources of drinking water. Natural gas extraction by hydraulic fracturing requires large amounts of water and all thermal power plants, including those powered by coal, gas, and oil, withdraw and consume water for cooling.

Biomass and geothermal power plants, like coal- and natural gas-fired power plants, require water for cooling. In addition, hydroelectric power plants impact river ecosystems both upstream and downstream from the dam. However, NREL's 80 percent by 2050 renewable energy study, which included biomass and geothermal, found that water withdrawals would decrease 51 percent to 58 percent by 2050 and water consumption would be reduced by 47 percent to 55 percent.

1.3 Different sources of Renewable Energy

1.3.1 Wind power

The movement in the atmosphere is driven by differences of temperature at the earth surface due to varying temperature of earth surfaces when lit by sunlight. Wind power can be used to pump water or generate electricity. Worldwide there are now many thousands of wind turbines functioning. Wind turbines can be used to harness the energy available in airflows. Current day turbines range from around 600 kW to 5 MW of rated power. Since the power output is a function of the cube of the wind speed, it increases rapidly with an increase in available wind velocity. Recent advancements have led to aerofoil wind turbines, which are more efficient due to a better aerodynamic structure.

1.3.2 Solar power

This form of energy relies on nuclear fusion power from the core of the sun. The energy can be collected and converted in a few different ways. The range is from solar water heating with solar collectors or attic cooling with solar attic fans for domestic use to the complex technologies of direct conversion of sunlight into electricity using mirrors or boilers or photovoltaic cells.

The tapping of solar energy owes its origins to the British astronomer John Herschel who famously used a solar thermal collector box to cook food during an expedition to Africa. Solar energy can be utilized in two major ways. Firstly, the captured heat can be used as solar thermal energy, with applications in space heating. Another alternative is the conversion of incident solar radiation to electrical energy, which is the most usable form of energy. This can be achieved with the help of solar photovoltaic cells or with concentrating solar power plants.

The figure shown below explains that the solar photovoltaic installation goes on increasing and due to increase in solar installation its production also goes on increasing.

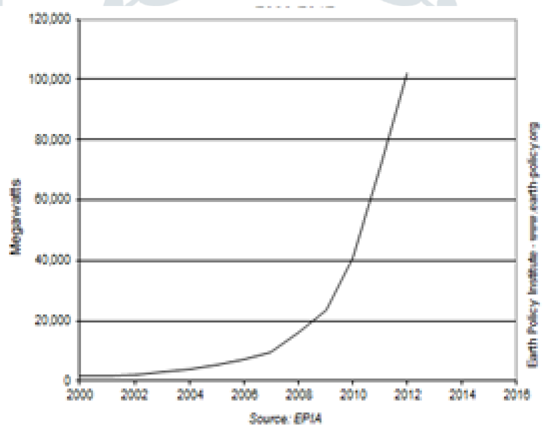

Figure1.1: World cumlative solar photovoltaic installations

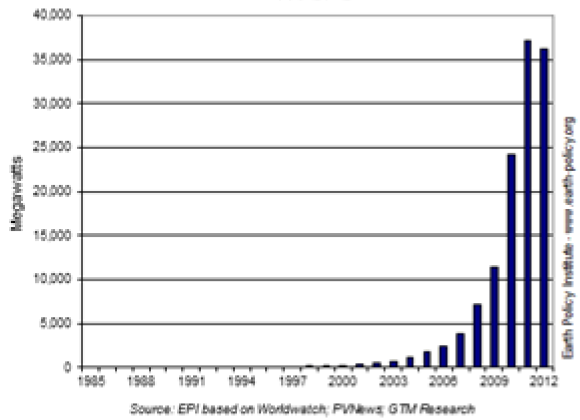

Figure1.2: World annual solar photovoltaic production

1.3.3 Small hydropower

This form uses the gravitational potential of elevated water that was lifted from the oceans by the sunlight. It is not strictly speaking renewable since all reservoirs eventually fill up and require very expensive excavation to become useful again. Hydropower installations up to 10MW are considered as small hydropower and counted as renewable energy sources. These involve converting the potential energy of water stored in dams into usable electrical energy through the use of water turbines. Run-of-the-river hydro electricity aims to utilize the kinetic energy of water without the need of building reservoirs or dams.

1.3.4 Biomass

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

1.3.5 Geothermal

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

1.3.6 Other forms of Energy

Energy from tides, the oceans and hot hydrogen fusions are the other forms that can be used to generate electricity.

1.4 Renewable energy trends across the globe

In Developed economies across the globe the Renewable energy utilization has been increasing. In last few years the continents like North America and Europe have embraced more renewable power capacity as compared to conventional power capacity. Renewable accounted for nearly 65% of newly installed power capacity in Europe and nearly 20% of annual power production. Recent advancements in solar photovoltaic technology and constant incubation of projects in countries like Germany and Spain have brought around tremendous growth in the solar PV market as well, which is projected to surpass other renewable energy sources in the coming years.

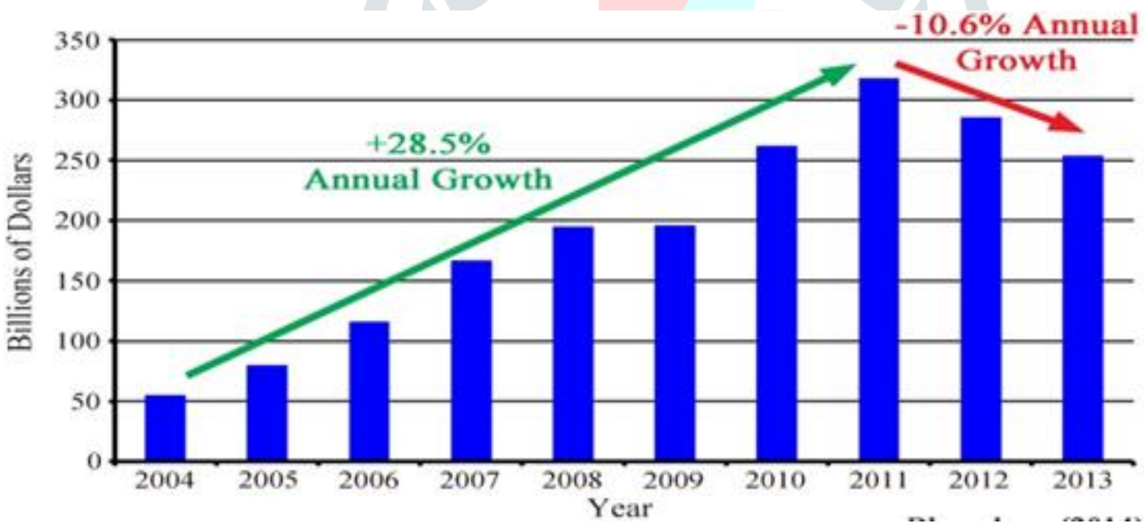

Figure1.3: Global investment in Renewable energy

As seen from the fig. 1.3 the investment in Renewable energy goes on increasing in last decades all over the globe.

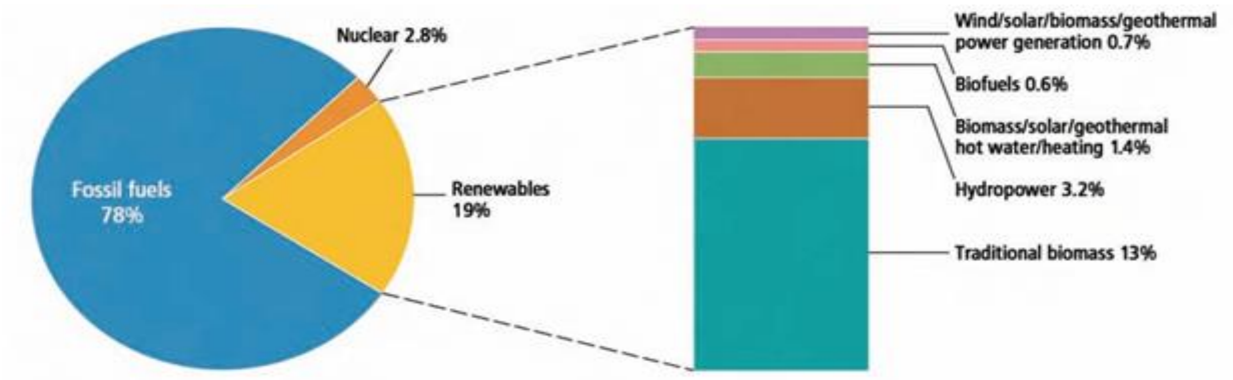

Figure1.4: Global Energy consumption

As seen from the Fig.1.4 Wind and Biomass occupies a major share of current energy consumption.

1.4.1 Energy Scenario in India

India is the fifth largest power generation portfolio in world currently. We are also the fifth largest Wind energy producer Wind energy accounts for nearly 70% (21.1 GW) of installed capacity. India is endowed with vast potential for solar energy and is rapidly emerging as a major manufacturing hub for solar power plants. It is expected that the annual PV-installed capacity will grow at a CAGR of around 49.5% between 2010 and 2014 to reach 1,500 MW by the end of 2014. The Government of India has set a capacity addition target of 30 GW, which will take the total renewable capacity to almost 55GW by the end of 2017. This includes 15 GW from wind power, 10 GW from solar power, 2.9 GW from biomass power and 2.1 GW from small hydro power. The government is playing an active role in promoting the adoption of renewable energy resources by offering various incentives, such as generation- based incentives (GBIs), capital and interest subsidies, viability gap funding, concessional finance, fiscal incentives etc. The National Solar Mission aims to promote the development and use of solar energy for power generation and other uses, with the ultimate objective of making solar energy compete with fossil-based energy options. The objective of the National Solar Mission is to reduce the cost of solar power generation in the country through long-term policy, large scale deployment goals, aggressive R&D and the domestic production of critical raw materials, components and products.

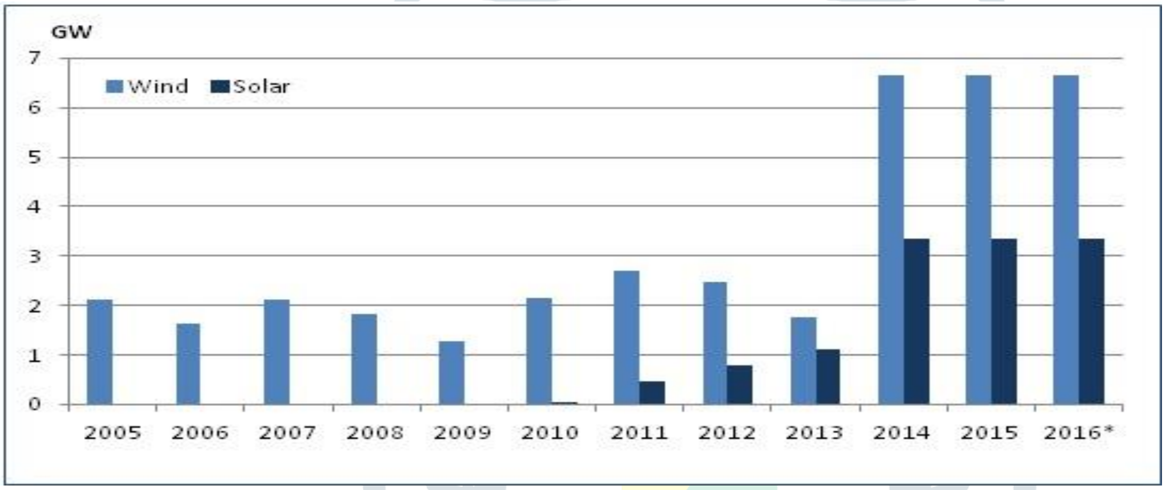

Figure 1.5: Generation by Wind and Solar

India is endowed with abundant of solar radiation. The country receives solar radiation equivalent to more than 5,000 trillion kWh/year, which is far more than its total annual energy requirement. The radiation available could be utilized for thermal as well as for photovoltaic applications. Solar thermal technologies have already found ready acceptance for a variety of decentralized applications in domestic, industrial and commercial sectors of the country. The most widely acceptable application is the solar water heating technology. However, solar steam generating and air heating technologies and energy efficient solar buildings are also attracting attention in urban and industrial areas.

1.5 Typical application of the PV system

A grid connected PV system consists of solar panels, one or several inverters, a power conditioning unit and grid connection equipment. They range from small residential and commercial roof top systems to large utility scale solar power stations. Unlike standalone power systems, a grid connected system rarely includes an integrated battery solution, as they are still very expensive.

Photovoltaic systems have become an energy generator for a wide range of applications. The applications could be standalone PV systems or grid connected PV systems. A standalone PV system is used in isolated applications where PV is connected directly to the load and storage system. With a standalone photovoltaic, when the PV source of energy is very large, having energy storage is beneficial.

Figure 1.6 shows a block diagram of typical hybrid renewable sources of energy. The integrated system has wind turbine and PV array as sources of energy. They are connected to the DC bus that could be connected to a different energy storage system, or inject the current directly with a DC/AC inverter. Therefore, the characteristic of energy storage for a PV system will be explained as well as some specification and standards for a grid connected PV system. A grid connected PV system is an electricity generating solar PV system that is connected to the utility grid.

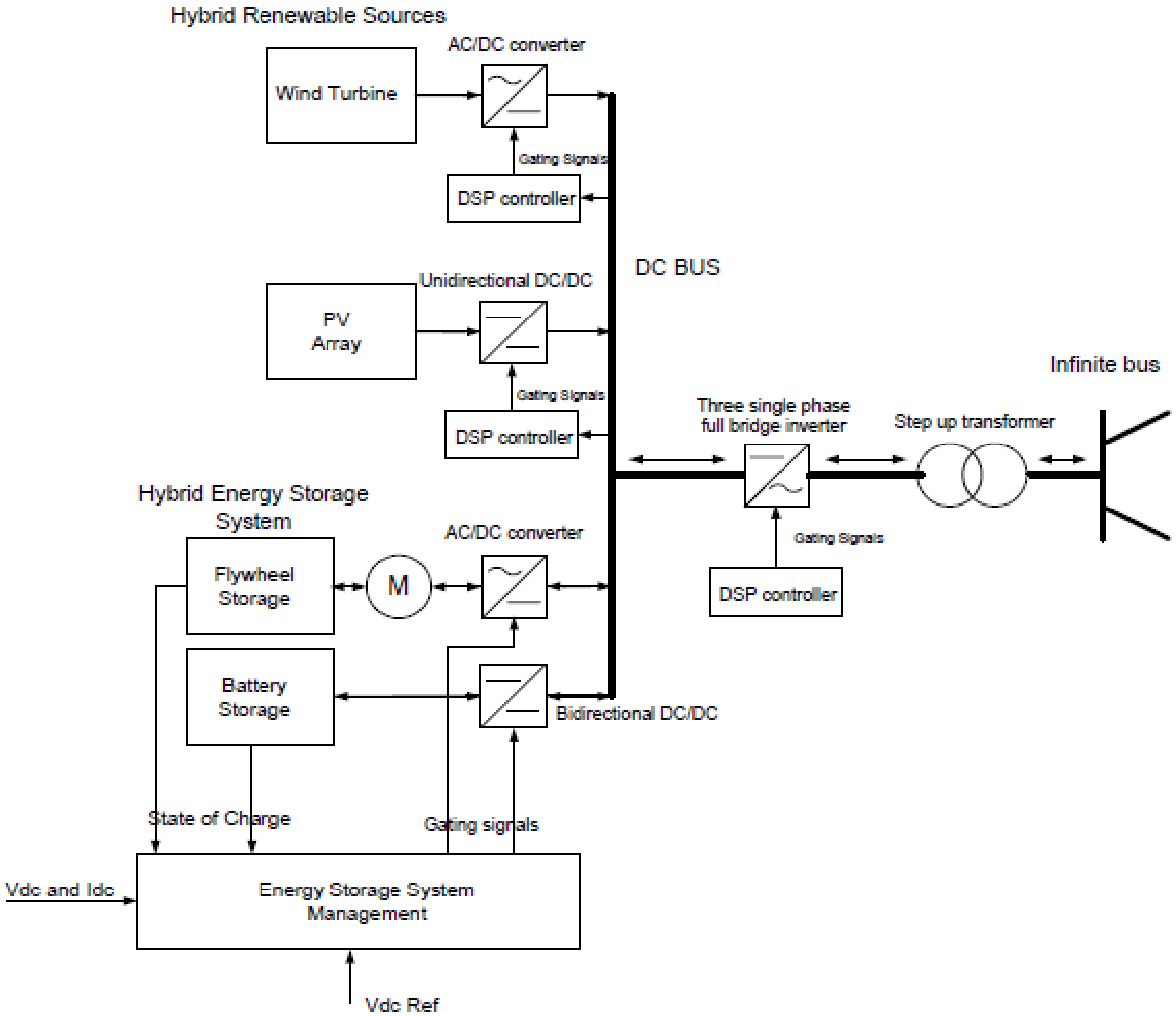

Figure1.6: Block Diagram of Renewable Energy System

1.6 Specification and Standards of Grid Connected Photovoltaic System

Power electronics inverters are necessary to transform into AC current then inject to the grid the energy delivered by the PV systems. Therefore, there are special standards and requirements concerning the connection of the PV to the grid. The rules and regulations set by the utility companies must be obeyed. These standards are to maintain the power quality produced by the photovoltaic distribution system. The grid-connected standards covered the topics about voltage, DC current injection, flicker, frequency, harmonics current, maximum current, total harmonics distortion (THD) and power factor. Some definitions used in grid connected PV are:

Islanding

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

Distributed resource islanding

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

Grounding

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

Voltage disturbances

The utility company set the voltage of grid network . The PV system cannot control the voltage of the grid so the output voltage of the PV has to be within the operating range defined by the standards. The inverters should detect abnormal voltages and prevent islanding of the system. The boundary limits of the voltage and the maximum trip time allowed for ceasing to energize the grid. The PV systems remain connected to the grid and should reconnect when the voltage was restored.

DC component injection

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

Total distortion harmonics

The topology has to be chosen along with the modulation scheme of the inverters should give an AC current with low level of harmonic distortion. High current harmonics can cause adverse effects on the diverse equipment connected to the grid. the maximum limit of acceptable distortion current the output harmonics current for six pulse inverters. "Total harmonic current distortion shall be less than 5% of the fundamental frequency current at rated inverter output. By increasing the pulse number of converters the order of dominant harmonics can be increased which can be easily filter out with the help of small size filters. Higher order harmonics are less dangerous than lower order harmonics.

Islanding protection

The inverters must have a feature that can identify a situation of islanding and respond accordingly to safeguard the people and equipment involved. For instance, the standard stated that the inverter should disconnect from the utility line when there is disturbance from the system.

In islanding, the inverters continue to supply local loads even in the case that the grid is no longer connected to the inverter.

1.7 Research Motivation

Steadily diminishing fossil fuel resources and long term planning for decreasing greenhouse gas emissions have promoted use of renewable energy resources over the past few decades. There are various types of renewable energy sources (RES) are available but solar energy and wind energy have become the most promising and attractive because of advancement in power electronic technique.

Photovoltaic systems are a key option among the available renewable energy sources. The abundant availability of the sun power in each country provides a better ground for deployment of PV systems as a potential energy resource. Moreover, distributed PV systems, in contrast to the other renewable energy sources such as wind power generators, are more easily integrated into the distribution grids at any point, for instance by installing at rooftops of buildings.

Photovoltaic (PV) sources are used nowadays in many applications as they own the advantage of being environmental friendly. In the past few years, solar energy sources demand has grown consistently due to the following factors:

1) Higher efficiency of solar cells

2) Improvement in Manufacturing Technique

3) Economies of scale

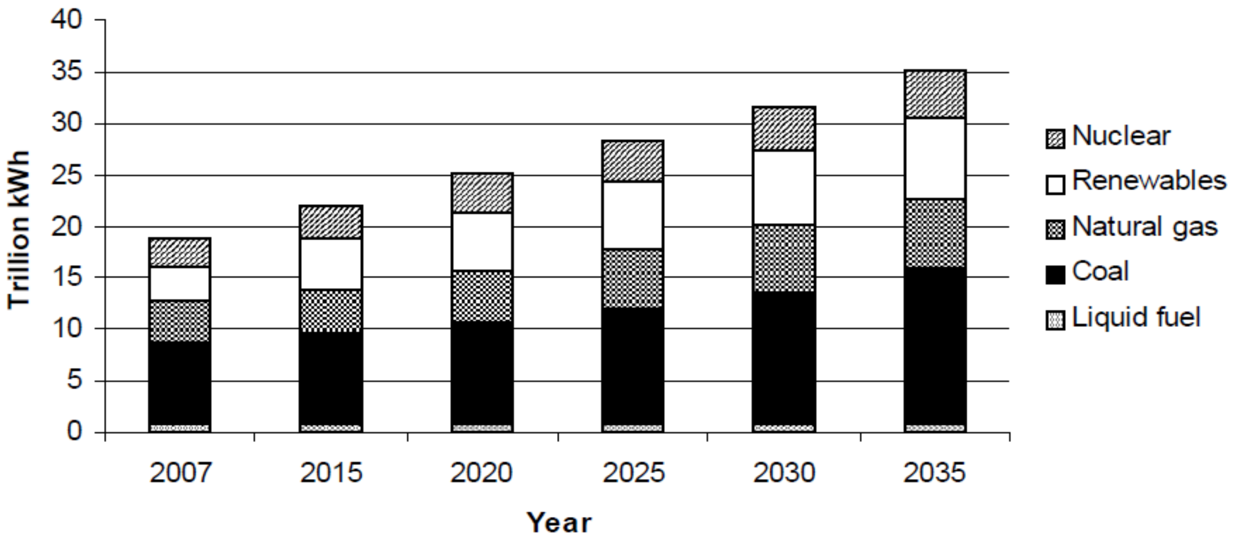

Figure1.7: World expected electricity production by fuel sources

The Renewable energy expected generation by 2035 is shown by the figure 1.7. It is clear that hydro and wind power dominates the share of renewable sources at 85% of the expected renewable energy contribution, while solar and geothermal energies are expected to contribute about 2% each. The cost per kWh of generated energy for solar power is high compared to fossil fuel based sources, which is why it does not contribute with a significant share. The grid connected photovoltaic system consists of solar panels, one or several inverters, grid connected equipments and a power conditioning unit. According to the International Energy Agency (IEA), about 5.56 GW of new PV capacity was installed in year 2008. This brought the total installed PV power in IEA participating countries to 13.4 GW. Around 96% of that capacity was installed in Germany, Spain, Italy, the United States of America, Korea and Japan. Grid connected photovoltaic compose the majority of that installed capacity.

Therefore most of the countries in world now focus on connecting more and more number of PV modules to the grid to get the advantage of solar energy. Now a day the largest PV power plant is more than 500MW all over the world. Topaz solar farm in United states and Desert Sunlight Solar Farm in United States has a capacity of 550MW. Furthermore, the output of PV arrays is influenced by solar irradiation and weather conditions. More importantly, the disadvantages such as high initial cost and limited life span of PV panels makes it more critical to extract as much power from them as possible. Therefore to extract maximum power from the PV array maximum power point tracking (MPPT) technique should be implemented in DC/DC converter. Several algorithms have been developed to achieve MPPT technique .As the capacity of PV system growing significantly, PV modules have the Impact on power grid which can't be ignored. They can cause problems on the grid like flicker, increase of harmonics, and aggravated stability of the power system. Especially when a large scale PV module is connected to the grid, the effects on the grid may be quite severe. Therefore, we must take care about the Impact of PV on grid.

Power Electronics plays an important role in power system now a days. Increasing use of static power converters like rectifiers and switched mode power supplies (SMPS) injects harmonics into the distribution system. Current harmonics produce voltage distortions, current distortions, and unsatisfactory operation of power systems. Therefore, harmonic mitigation plays an essential role in grid connected PV system. IEEE Std. 519 was first introduced in 1981 and most recently revised in 1992 to provide direction on dealing with harmonics produced by static power converters and nonlinear loads. This standard helps to overcome the negative effect of harmonics on the utility grid. In this thesis, as well as supplying active power, PV inverter can be controlled to provide harmonic currents needed by nonlinear loads so that the current on the grid side can be approximately sinusoidal, at least complies with the IEEE Std.519. This concept is simulated successfully in the simulation environment. The output of solar photovoltaic array dependent on the level of solar irradiance and surface temperature of the array itself. Maximum power output from the array can be achieved by a combination of mechanical solar trackers to maximize the amount of light received, and a maximum power point tracking (MPPT) algorithm is used to operate the PV array around its maximum power output for a given load under varying atmospheric conditions. For a fixed load the task of MPPT is impedance matching, where as a power electronic DC/DC converter tries to match the load impedance to the ratio between voltage and current of the array at the maximum power point (MPP). One of the most common algorithms to achieve this task is the Perturb and Observe (P&O) algorithm. It perturbs the duty cycle of the DC/DC converter switch and then observes the resulting change on the delivered power to the load. The algorithm performs this systematically until any resulting change in the duty cycle causes the power delivered to the load to decrease.

While in grid connected systems the situation is different since the load impedance is not fixed. A fast MPPT algorithm is required to reach maximum power output from the array under load and weather variations. the incremental conductance technique is faster than P&O, but it is still relatively slow for grid connected applications as it performs computations that help it keep the sense of direction towards the maximum power point.

The aim of the thesis is to estimate the PV array voltage at the maximum power point using test cells which keep track of the current radiation and temperature levels, and then use this information to drive the main PV array to maximum power output. This technique is simple and offers fast dynamic response to variations in atmospheric conditions. But it does so by approximating the MPP of the array.

1.8 Objective of the thesis

The goal of research done in this thesis is to develop a control strategy for three phase grid connected photovoltaic solar cell arrays. This can be summarized in the following points:

1. Use the equivalent circuit model of a PV cell to build and simulate a grid connected PV system using the open loop MPPT technique described earlier. The response to a simulated weather change depicted by a drop in solar irradiation will be investigated. The dynamic response of the algorithm is characterized by the speed it drives the PV system into maximum power operation while ensuring that the injected current remains in phase with the grid voltage to achieve a unity power factor.

2. Design of Boost converter which is required to step up the voltage obtained from the PV system because the voltage obtained is quite low . The control signals will be used to drive a three phase voltage source inverter (VSI) to regulate the power conversion process from DC to AC. Harmonics that result during the power conversion process should be prevented from propagating into the power system grid because of their negative effects on the power system equipment and power quality.

1.9 Future Applications

Over the past few decades, the photovoltaic (PV) market has grown radically and the price for PV systems has decreased rapidly due to technology development in solar cell manufacture and performance improvement on efficiency conversion. Nowadays, PV systems are usually used in three main fields:

(1) Satellite applications, where the solar panels provide power to satellite.

(2) Off-grid applications, where solar arrays are used to power remote load that are not connected to power grid.

(3) Grid-connected applications, in which solar arrays are used to supply solar energy to local loads as well as the electric grid.

As the increasing installation of grid-connected PV systems, especially large systems in the order of megawatts, might lead to some operational problems in the electric network. Such negative impacts include power and voltage fluctuation problems, harmonic distortion, malfunctioning of protective devices and so on. This may still prevent further share of grid-connected PV system in electricity market. Therefore, studying the possible impacts of PV systems on the electric network is and will be becoming an important issue and receiving a lot of attention from both researchers and electric utilities. For example, different algorithms are developed to mitigate the harmonics injected into the electric network. Active power filter is one of the most used methods. However, the algorithm discussed in the thesis is the most simple, effective and easy to implement.

And more research will also focus on dynamic response and system performance when interfaced with power grid, like sudden grid voltage change, system fault both in AC and DC side, solar irradiation change and etc. Various control schemes have been developed to detect faults and to protect devices and the system. For instance, anti islanding scheme has been equipped for solar energy interfaced with utility system to ensure personnel safety and power quality.

CHAPTER 2
LITERATURE REVIEW

A large number of reference books are available in the field of solar PV system and its integration with grid, which have been listed in the references given at the end of the thesis. Brief content of some of them are given below:

Liu Weiping et al. in his paper [1] Research and Application of High Concentrating Solar Photovoltaic System, describes concentrating photovoltaic power generation system technical problems and its analysis, and put forward improvement scheme. Using the solar energy focusing photovoltaic generate electricity is the effective way of solving current questions about shortage of energy exhaustion of resources, environmental pollution and so on Under the condition of the same output power of the photovoltaic system, using low cost superiority of the high concentrator material in place of the expensive solar cell to reduce the comprehensive cost of the photovoltaic system and realize the highly effective and the efficient unification of the focusing photovoltaic system.

Marcelo G. Molina et al. in his paper [2] Improved Power Conditioning System for Grid Integration of Photovoltaic Solar Energy Conversion System, describes the power electronics technology plays a vital role in managing an effective grid integration of the PV system, since it is subject to requirements related not only to the intermittent source itself but also to its effects on the grid operation. This paper proposes an improved structure of power conditioning system (PCS) for the grid integration of PV solar systems. The topology employed consists of a three-level cascaded Z-source inverter and allows the flexible, efficient and reliable generation of high quality electric power from the PV array. The increasing utilization of photovoltaic (PV) solar systems in distributed (or dispersed) generation systems imposes new requirements for the operation and management of the distribution grid, especially when high penetration levels are achieved.

Rabeh Abbassi et al. in his paper [3] Improvement of the Integration of Grid Connected Wind-Photovoltaic Hybrid System, describes the control strategies for the integration of a grid-connected wind-photovoltaic hybrid system via adaptation converters connected to a common DC bus. For both wind and solar system, adequate control algorithms have been implemented for the maximum power extraction. This paper also explains that the grid side converter (GSC) was made in order to control the power quality and quantity of the feed power to the grid.

Michel Vandenbergh et al. in his paper [4] Technical Solutions Supporting The Large Scale Integration Of Photovoltaic Systems In The Future Distribution Grids, describes the technical solutions for increasing the grid hosting capacity and then the suitability of technical solutions have been identified. In order to increase the grid hosting capacity for PV integration, the main limitation is the voltage increase along the feeders due to higher generation power than demand.

M.Z.C Wanik et al. in his paper [5] Simplified Dynamic Model Of Photovoltaic Generation System For Grid Integration Studies, describes a simplified mathematical model of photovoltaic generation system which can be used to perform various power system studies. First the relation between solar radiation and PV output is presented. Then the power electronics inverter control employed in PV system is described. Finally the performance of detail model and simplified model of PV system is compared and commented. The usage of this simplified model will reduce the complexity in modeling and will reduce substantially power system study time.

Aarti Gupta et al. in his paper [6] Grid Integrated Solar Photovoltaic System Using Multi-level Inverter, describes that a inverter is a critical component responsible for the control of electricity flow between the dc source, and loads or grid. This paper presents a solar PV generation system integrated to the grid. The results of matlab modeling of the system detail the comparative operation of inverter topologies which are the conventional two level inverters and multilevel inverter topology to reduce total harmonic distortions in grid voltage and electromagnetic

interference. The three levels inverter generates three-phase voltages and currents which are sinusoidal and balance. The total harmonic distortion of voltage and current in grid tie three level inverter system in reduced to a large extent than the two level one. And they provide reactive power compensation at PCC and reduced electromagnetic emission.

Vaddi Ramesh et al. in his paper [7] Simulation And Implementation Of Incremental Conductance MPPT With Direct Control Method Using Boost Converter, describes to decrease the usage of limited conventional energy sources and to increase the non-conventional energy sources like solar energy. Compared to other Non-conventional energy sources P.V system is more efficient. Due to variations of atmospheric temperature and radiation P.V Array does not operate at M.P.P to give maximum power and results in low efficiency. Short Circuit Current is one of the simple M.P.P.T algorithms but, does not exactly operate at M.P.O.P. Solar cells in PV array work only in part of volt-ampere Characteristic near working point where maximum voltage and maximum current is. This work gives the best results maintaining the maximum power at different temperature and solar irradiance conditions.

D.V.Pavan Kumar et al. in his paper [8] Attaining Balanced Power from PV Module Using Incremental Conductance Method, describes an excellent solution for attaining balanced power from PV module. The output power of the PV module changes continuously as it depends upon the existing sunlight in the surrounding PV installation. So we need a control on the output power obtained from PV modules in order to balance and stabilize the power which is ultimately supplied to the grid. In this paper a single phase photovoltaic system with shunt controller functionality has been presented. The PV converter is voltage controlled with a repetitive algorithm. An MPPT algorithm has been specifically designed for the proposed voltage controlled converter. It is based on the incremental conductance method and it has been modified to change the phase displacement between the grid voltage and the converter voltage maximizing the power extraction from the PV panels. Burri Ankaiah et al. in his paper [9] MPPT Algorithm for Solar Photovoltaic Cell by Incremental Conductance Method, describes Investigation of Incremental conductance Based maximum Power Point Tracking for Photovoltaic System, to have the advantages of low frequency switching. It is important to operate PV energy conversion systems near the maximum power point to increase the output efficiency of PV arrays. The output power of PV arrays is always changing with weather conditions, i.e., solar irradiation and atmospheric temperature. Therefore, a MPPT control to extract maximum power from the PV arrays at real time becomes indispensable in PV generation system.

A.Shanmughapriya et al. in his paper [10] Synchronization Of Power From Grid And PV System With M.p.p.t. Based On Incremental Conductance Technique, describes the simple MPPT method is included to increase the efficiency of the output because this method needs only the calculation of the conductance. So that the output power from the array is increased and the power taken from the EB is decreased. This method reduces the amount of power taken from the EB so that the tariff amount is low compared to the normal method. The drawback of this method is the synchronization of power is difficult task. The future development can also be made by the excess power generated by this method is synchronized with the grid. In this paper the proposal is that the system management of hybrid system to load. It has been done by using the MATLAB software. In this paper Incremental Conductance based MPPT for photovoltaic system is done for the development of solar technologies and power from both EB as well as solar are managed efficiently to get the optimum usage of power.

Trishan Esram et al. in his paper [11] Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques, describes many different techniques for maximum power point tracking of photovoltaic (PV) arrays. The techniques are taken from the literature dating back to the earliest methods. It is shown that at least 19 distinct methods have been introduced in the literature, with many variations on implementation. This paper should serve as a convenient reference for future work in PV power generation. Several MPPT techniques taken from the literature are discussed and analyzed herein, with their pros and cons.

Lokin Joshi in his paper [12] Incremental Conductance Based Maximum Power Point Tracking for PV Multi-string Power Conditioning System, describes Multi-string Power Conditioning System for PV application and Maximum Power Point Tracking. This paper includes the results performed in PSIM-9 software such as Performance comparison of Incremental Conductance MPPT method with fixed step size and variable step size under varying irradiation conditions. The photovoltaic Multi string power conditioning system with MPPT control using fixed step size and variable step size incremental conductance method have been analyzed by simulation. The fixed step-size incremental conductance algorithm can't meet tracking speed and steady-state accuracy of the PV system simultaneously, the value of tracking step-size is determined by the system performance requirements.

E. Ortjohann et al. in his paper [13] Multi-Level Hierarchical Control Strategy for Smart Grid Using Clustering Concept, describes a multi-level hierarchical control strategy for efficient grid control for the distributed generation units. This proposed control strategy provides availability and reliability for future power systems. Recently, the distributed generation (DG) based on renewable energy sources (RESs) is quickly penetrating and integrating into the power systems. Moreover, a large number of intelligent infrastructures are installed into the power systems in order to establish a future power system, called smart grid. However, the increased grid integration of these sources leads to significant structural changes for grid automation and control. This paper introduces the concept of multi-level SC strategy for clustered power grids. It enables joint action of RESs and DERs, empowers them to actively participate in grid control and take over control functionalities of the conventional centralized power plants.

E. M. Natsheh et al. in his paper[14] Modeling and Control of Smart Grid Integration of Solar/ Wind energy conversion system, describes a novel model of smart grid-connected PV/WT hybrid system. It comprises photovoltaic array, wind turbine, asynchronous (induction) generator, controller and converters. The model is implemented using MATLAB/SIMULINK software package. Perturb and observe (P&O) algorithm is used for maximizing the generated power based on maximum power point tracker (MPPT) implementation. The dynamic behavior of the proposed model is examined under different operating conditions. Solar irradiance, temperature and wind speed data is gathered from a grid connected, 28.8kW solar power system located in central Manchester. Real-time measured parameters are used as inputs for the developed system.

Subrata Mukhopadhyay et al. in his paper[15] On the Progress of Renewable Energy Integration into Smarts Grid in India, describes Renewable coming as big source of electric energy and due to its high potentials, particularly in the areas of wind and solar power, in the years to come it will form sizable part of generation feeding the grid. However, as it comes with unpredictable and variable contribution, while integrating smart grid utilizing advanced technologies of digital computing and communication has to operate and control the power system within the acceptable ranges of parameters. Regulatory mechanism in India, some already in vogue and others gradually coming to be in force encourages to promote Distributed Generation and Renewables and protects the concerned Green Energy Sources to meet the electricity demand at every instant of time along with centralized conventional thermal or nuclear generation.

Arup Sinha et al. in his paper[16] Smart Grid Initiatives for Power Distribution Utility in India, describes Smart Grid is sophisticated, digitally enhanced power systems where the use of modern communications and control technologies allows much greater robustness, efficiency and flexibility than today's power systems. A smart grid impacts all the components of a power system especially the distribution level. One subset of smart grids is smart metering / advanced metering infrastructure (AMI) etc. In a smart grid, all the various nodes need to interconnect to share data as and where needed. Smart Grid envisages providing choices to each and every customer for deciding the timing and amount of power consumption based upon the price of the power at a particular moment of time, apart from providing choices to the consumer and motivating them to participate in the operations of the grid.

Aaron St. Leger et al. in his paper[17] Smart Grid Modeling Approach for Wide Area Control Applications, describes an approach for modeling smart grids for wide area control applications. More specifically, it is proposed to model smart grids as a set of interdependent composite networks. A composite network is one whose evolution in time and/or space is described as a composition of more than one category of networks. The modeling methodology is based on the initial partitioning by the National Institute of Standards and Technology (NIST) of the smart grid domains. And then presents a generator set point over a communication link.

Mrs. N. V. Vader et al. in his paper [18] System Integration: Smart Grid with Renewable Energy, describes As electricity demands are increasing day by day causing unbalance in the present grid system which results in various causes like load shedding, unbalance voltage etc which ultimately affects the consumers. Now to avoid all such situations the only option is to meet the demand by increasing generation but, we are also lagging with the conventional sources so generating more power is also not convenient by conventional ways. Thus, use of Renewable is quite important. The solar power reaching the earth's surface is about 86,000 TW. Covering 0.22% of our planet with solar collectors with an efficiency of 8% would be enough to satisfy the current global power consumption solar have tremendous potential for fulfilling the world's energy needs.

E. Bitar et al. in his paper [19] Systems and Control Opportunities in the Integration of Renewable Energy into the Smart Grid, describes some of these systems and control research opportunities that arise in the deep integration of renewable energy sources. The Smart Grid is among the most important and ambitious endeavors of our time. Deep integration of renewable energy sources is one component of the Smart Grid vision. A fundamental difficulty here is that renewable energy sources are highly variable they are not dispatchable, are intermittent, and uncertain. The electricity grid must absorb this variability through a portfolio of solutions. These include aggregation of variable generation, curtailment, operating reserves, storage technologies, local generation, and distributed demand response. The various elements in this portfolio must be dynamically coordinated based on available information within the framework of electricity grid operations.

Er. Alekhya Datta et al. in his paper [20] Accelerated Deployment of Smart Grid Technologies in India – Present Scenario, Challenges and Way Forward, describes As an immediate way forward, there is a need for a strong institutional framework that can drive Smart Grid development in India. To begin with, ISGTF needs to be supported by the permanent, independent members including industry experts in respective areas on deputation from different entities, and with

the whole-time engagement of appropriate man-power who will work exclusively for Smart Grid deployment in India. In order to effectively implement the goals conceived in the Smart Grid Vision and Roadmap for India, there should be unanimity in launching a National Smart Grid Mission (NSGM) for India.

CHAPTER-3

COMPONENTS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

The aim of this chapter is to present an overview of the main building blocks in a grid connected PV system. These systems can be classified in terms of their connection to the power system grid into the following:

1. Off-grid residential: This class of photovoltaic systems is used to power small homes that are not connected to the power system grid. The output of the system is used for lighting and refrigeration and other basic power needs. The capacity of the system is below 10 kW in peak output power. They are used when it is more economical to install a PV system than extending the power lines to locations that are far from the utility.

2. Off-grid commercial: PV systems that are used for commercial purposes, for example water pumping or for generating power to run telecommunication towers. The great need for power in these remote locations makes installing PV systems an economically viable alternative.

3. Grid-Connected distributed: Systems installed on rooftops of homes and buildings that sell power back to the power system. Smart meters are used to keep track of the net power, which is the difference between customer generated power and consumed power. The capacity of the system varies depending on the available surface area for PV installation.

4. Grid-connected centralized: Utility scale systems that can reach tens of megawatts of power output under optimum conditions of solar irradiation. These systems are usually ground mounted and span a large area for power harvesting.

As centralized grid connected PV systems comprise a large portion of the installed capacity, focus in this thesis will be mainly on it to study their performance and interactions with the power system grid.

Several components are needed to construct a grid connected PV system to perform the power generation and conversion functions, as shown in figure 3-1. A PV array is used to convert the light from the sun into DC current and voltage. A DC converter is connected to the PV array to increase its terminal voltage and provide the means to implement an MPPT technique by controlling its switching duty cycle. The output power from the array is stored temporarily in large capacitors to hold power before DC/AC power conversion. A three phase inverter is then connected to perform the power conversion of the array output power into AC power suitable for injection into the grid. Pulse width modulation control is one of the techniques used to shape the magnitude and phase of the inverter output voltage. A harmonics filter is added after the inverter to reduce the harmonics in the output current which result from the power conversion process. An interfacing transformer is connected after the filter to step up the output AC voltage of the inverter to match the grid voltage level. Protection relays and circuit breakers are used to isolate the PV system when faults occur to prevent damage to the equipment if their ratings are exceeded.

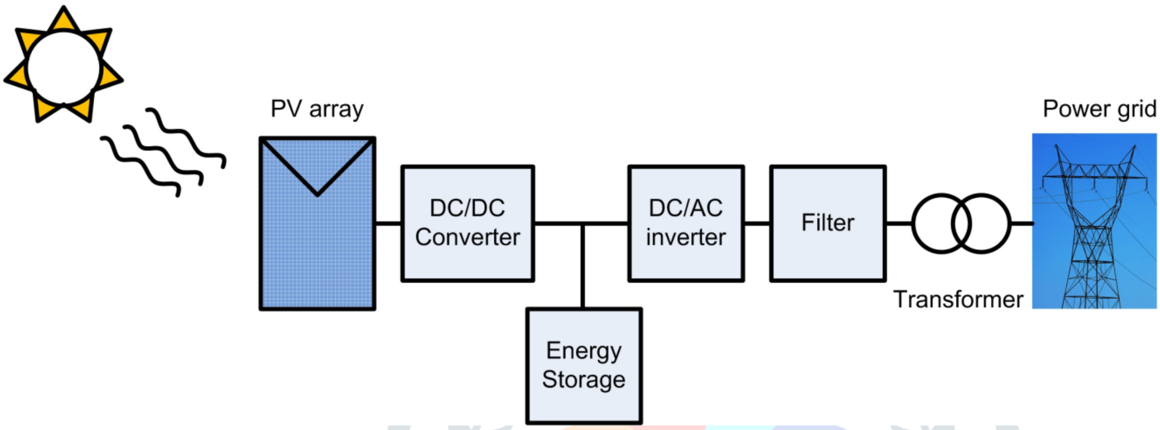

Figure 3.1: Components of a grid connected PV system.

3.1 Photovoltaic Cell Technology and Modeling

A photovoltaic cell or photoelectric cell is a semiconductor device that converts light to electrical energy by photovoltaic effect. If the energy of photon of light is greater than the band gap then the electron is emitted and the flow of electrons creates current. However a photovoltaic cell is different from a photodiode. In a photodiode light falls on n channel of the semiconductor junction and get converted into current or voltage signal but a photovoltaic cell is always forward biased.

PV cells are classified based on the type of materials used in manufacturing them.. Photovoltaic cells are made of silicon and other semiconductor materials. Below are some of the common materials used to build PV cells.

3.1.1 Crystalline Silicon PV cells

Comprising 20% of the earth's crust composition, Silicon is considered the second most abundant element on earth. Silicon exists in nature in the form of Silicon dioxide minerals like quartz and silicate based minerals. It has first to reach a high degree of purity before it can be used for manufacturing single crystal PV cells. High grade quartz or silicates are first treated chemically to form an intermediate silicon compound (Liquid trichlorosilane $SiHCl_3$), which is then reduced in a reaction with hydrogen to produce chunks of highly pure Silicon, about 99.9999% in purity. After that, these chunks of silicon are melted and formed into a single large crystal of Silicon through a process called the Czochralski process. The large Silicon crystal is then cut into thin wafers using special cutting equipment. These wafers are then polished and doped with impurities to form the required p-n junction of the PV cell. Antireflective coating materials are added on top of the cell to reduce light reflections and allow the cell to better absorb sunlight. A grid of contacts made of silver or aluminum is added to the cell to extract the electric current generated when it is exposed to light. The experimental efficiency of Single crystal silicon cells is about 25% or slightly higher under standard test conditions (1000 W/m^2 and 25 °C). However, commercial PV modules' efficiency is in the range of 12%-15%. The process of producing PV cells using this technology is quite expensive, which led to development of new technologies that do not suffer from this drawback.

3.1.2 Multi-crystalline Silicon PV cells

In order to avoid the high cost of producing single crystal solar cells, cheaper multi-crystalline cells were developed. As the name implies, multi-crystalline Silicon solar cells do not have a single crystal structure. They are rather derived from several smaller crystals that together from the cell. The grain boundaries between each crystal reduce the net electric current that can be generated because of electron recombination with defective atomic bonds. However, the cost of manufacturing cells using this technology is less than what would be in the case of a single crystalline cell. The efficiency of modules produced using this technology ranges from 11%-14%.

3.1.3 Thin Film PV cells

Thin film PV cells are manufactured through the deposition of several thin layers of atoms or molecules of certain materials on a holding surface. They have the advantage over their crystalline Silicon counterparts in their thickness and weight. They can be 1 to 10 micrometers thin as compared to 300 micrometers for Silicon cells. Thin film PV cells do not employ the metal grid required for carrying current outside the cell. However, they make use of a thin layer of conducting oxides to carry the output current to the external circuit. The electric field in the p-n junction of the cell is created between the surface contacts of two different materials, creating what is called a hetero junction PV cell. Thin film PV can be integrated on windows and facades of buildings because they generate electricity while allowing some light to pass through. Two common thin film materials are Copper indium diselenide (CIS for short) and Cadmium Telluride (Cd-Te). CIS thin films are characterized by their very high absorptive. PV cells that are built from this material are of the hetero junction type. The top layer can be cadmium sulfide, while the bottom layer can be gallium to improve the efficiency of the device. However the resistivity of p-type CdTe is quite high therefore increasing the internal losses. This issue can be addressed through the use of intrinsic Cd-Te while using a layer of zinc telluride between the cell and back the contacts. Efficiency for these technologies is about 10-13%.

3.2 Photovoltaic cell equivalent model circuit

The PV cell equivalent model is required to simulate its behavior. One of the models proposed in literature is the double exponential model depicted in figure 3.2. Using the physics of p-n junctions, a cell can be modeled as a DC current source in parallel with two diodes that represent currents escaping due to diffusion and charge recombination mechanisms. Two resistances, R_S and R_P, are included to model the contact resistances and the internal PV cell resistance respectively. The values of these two resistances can be obtained from measurements or by using curve fitting methods based on the I-V characteristic of the cell.

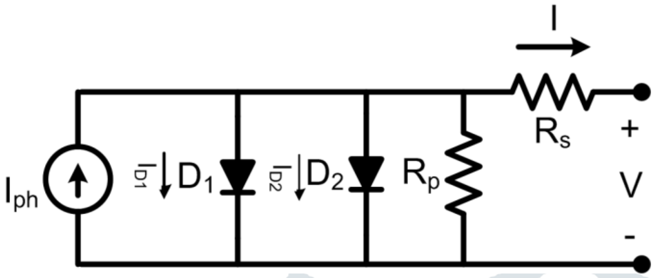

Figure 3.2: Double exponential PV cell model.

The relationship between the PV cell output current and terminal voltage is governed by:

$$I = I_{ph} - I_{D1} - I_{D2} - \frac{V + IR_s}{R_p}$$

$$I_{D1} = I_{01}\left[e\left(\frac{q(V + IR_s)}{akT}\right) - 1\right]$$

$$I_{D2} = I_{02}\left[e\left(\frac{q(V + IR_s)}{akT}\right) - 1\right]$$

Where I_{ph} is the PV cell internal generated photocurrent, I_{D1} and I_{D2} are the currents passing through diodes D_1 and D_2, a is the diode ideality factor, k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K) T is the cell temperature in degrees Kelvin, q is the electron charge ($1.60217646 \times 10^{-1}$C), I_{01} and I_{02} are the reverse saturation currents of each diode respectively.

Assuming that the current passing in diode D_2 due to charge recombination is small enough to be neglected, a simplified PV cell model can be reached as shown in fig 3-3.

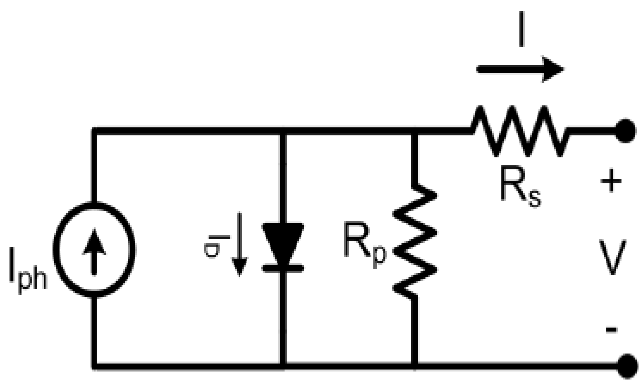

Figure 3.3: Simplified PV cell model.

This model provides a good compromise between accuracy and model complexity. In this case, current I_{D2} can be omitted from above equations and the relation simplifies to:

$$I = I_{ph} - I_0 \left[e\left(\frac{q(V+IR_S)}{akT}\right) - 1 \right] - \frac{V+IR_S}{R_p}$$

It is clear that the relationship between the PV cell terminal voltage and output current is nonlinear because of the presence of the exponential term in the above equations. The presence of the p-n semiconductor junction is the reason behind this nonlinearity. The result is a unique I-V characteristic for the cell where the current output is constant over a wide range of voltages until it reaches a certain point where it start dropping exponential. The I-V characteristic of a 200 W PV module by Kyocera is shown in figure 3-4.

A PV module is the result of connecting several PV cells in series to order to increase the output voltage. The characteristic has the same shape except for changes in the magnitude of the open circuit voltage.

Another important relationship in PV cells is the power-voltage characteristic. The product of multiplying the current and voltage is evaluated at each point in the curve to find out how much power can be obtained as voltage changes.

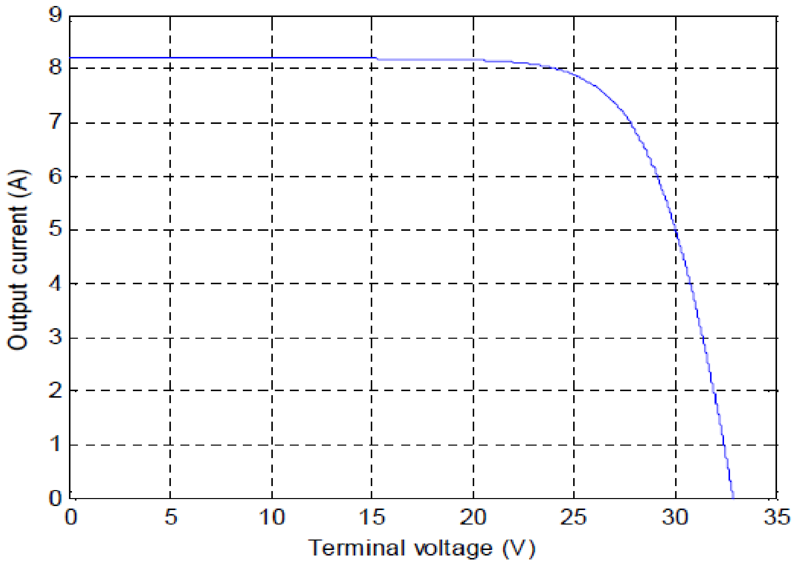

Figure 3.4: I-V characteristic of a Photovoltaic module

The power-voltage relationship for the PV module is depicted in figure 3-5. Initially, power starts increasing as voltage increases. A certain point in the curve is reached where maximum power output can be obtained; this point is therefore referred to as the Maximum Power Point (MPP). After this point, power starts dropping as the terminal voltage increases until it eventually reaches zero at open circuit voltage. Power output from a PV cell is dictated by the magnitude of the load resistance, defined by the division of the cell voltage over current, in case of fixed loads. If the load impedance does not equal the value required to extract maximum power, then it is possible to use a switched mode DC converter to do the matching between the PV cell and the load. The process of changing the PV array terminal voltage externally to extract maximum power for different loads is known as Maximum Power Point Tracking (MPPT).Several techniques can be used to perform this task as will be explained in a following section of the thesis.

The PV cell characteristics also depend on external factors including temperature and solar irradiation level.

To incorporate these effects into the model, two additional relations are used.

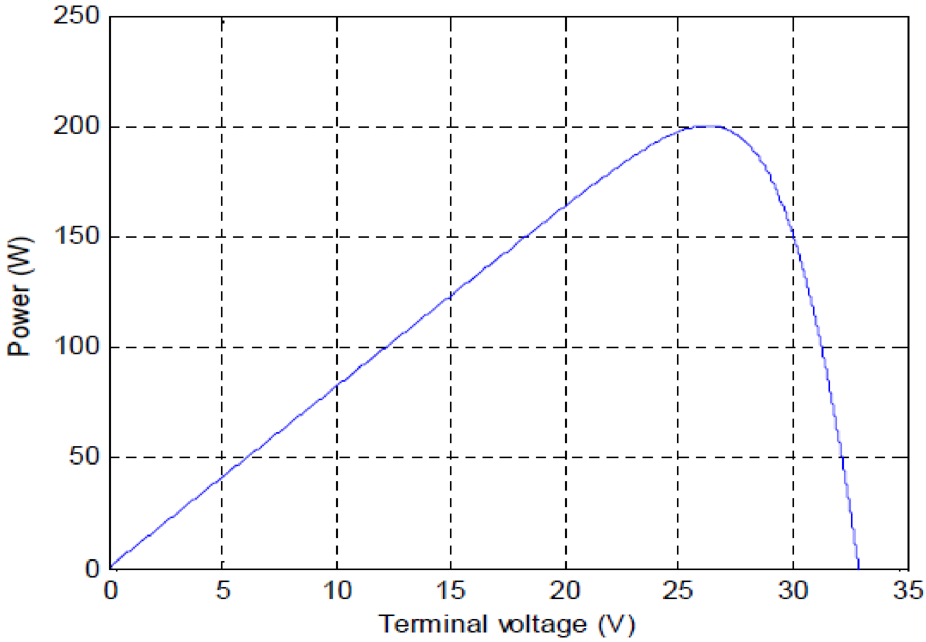

Figure 3.5: Power-Voltage relationship of a PV module

Output current varies with solar irradiation and temperature through:

$$I= (I_n+K_1\Delta T)\frac{G}{Gn}$$

where I_n is the nominal PV cell output current (at 25 °C and 1000 W/m^2), K_I is the current/temperature variation coefficient (A/°C), ΔT is the variation from the nominal temperature (25°C) and G_n is the nominal solar irradiation (1000 W/m^2). The value of K_I is relatively small and this makes the cell output current linearly dependent on solar radiation level more than temperature. The effect of solar irradiation and temperature on the characteristics of the PV module is depicted in figures 3-6, 3-7, 3-8 and 3-9. To investigate the effect of solar irradiation on the currents and voltages of the module, temperature was held constant at 25 °C and the resulting I-V and P-V characteristics were plotted. Figure 3-6 shows the I-V characteristics of the module at different irradiation levels of 500, 800 and 1000 W/m2. The P-V characteristics are shown in figure 3-7 for the same irradiation levels mentioned.

It is noticed that output current is directly proportional to changes in solar irradiation as expected from the model. Maximum output power of the module is reduced by half when the solar irradiation drops to 500 W/m2. However, the open circuit voltage does not change significantly. To find out the effect of temperature on the module performance, solar irradiation level was assumed constant at 1000 W/m2 while allowing temperature to vary between 25 and 80 °C. The result is shown in figures 3-8 and 3-9 for the I-V and P-V characteristics as temperature was set to 25, 60 and 80 °C respectively. The open circuit voltage of the module decreases as surface temperature increases. Current, on the other hand, increases slightly with temperature. The maximum power output of the module reduces as the surface temperature rise.

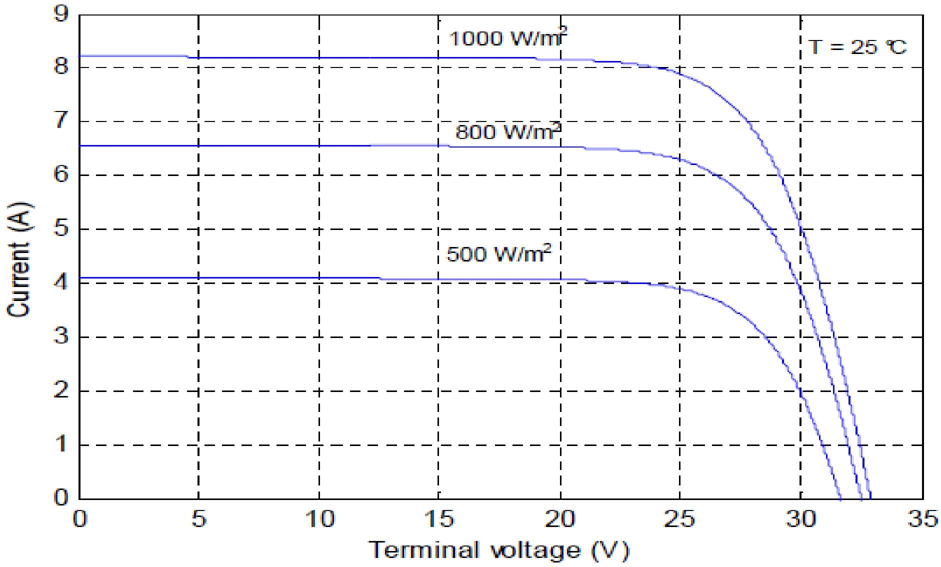

Figure 3.6: I-V characteristics of the PV module under different solar irradiation levels

The above figure shows the I-V characteristics of the PV module under different solar irradiation level. As the solar irradiation level changes the I-V characteristics of the PV module changes. The figure 3-7 shows the PV characteristics of the photovoltaic module under different solar irradiation levels.

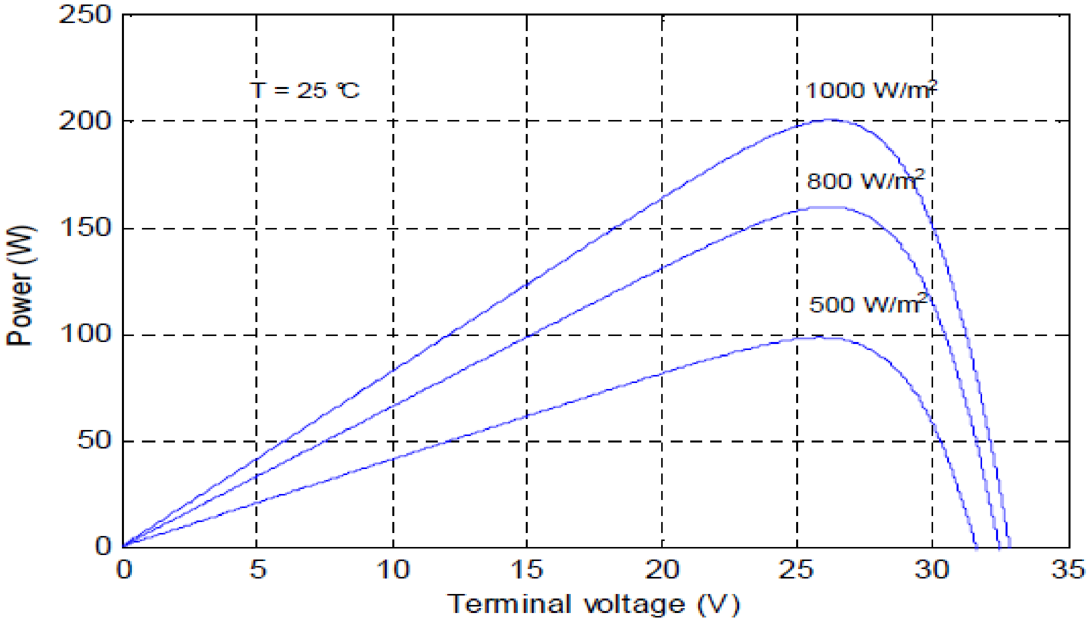

Figure 3.7: P-V characteristics of the PV module under different solar irradiation levels

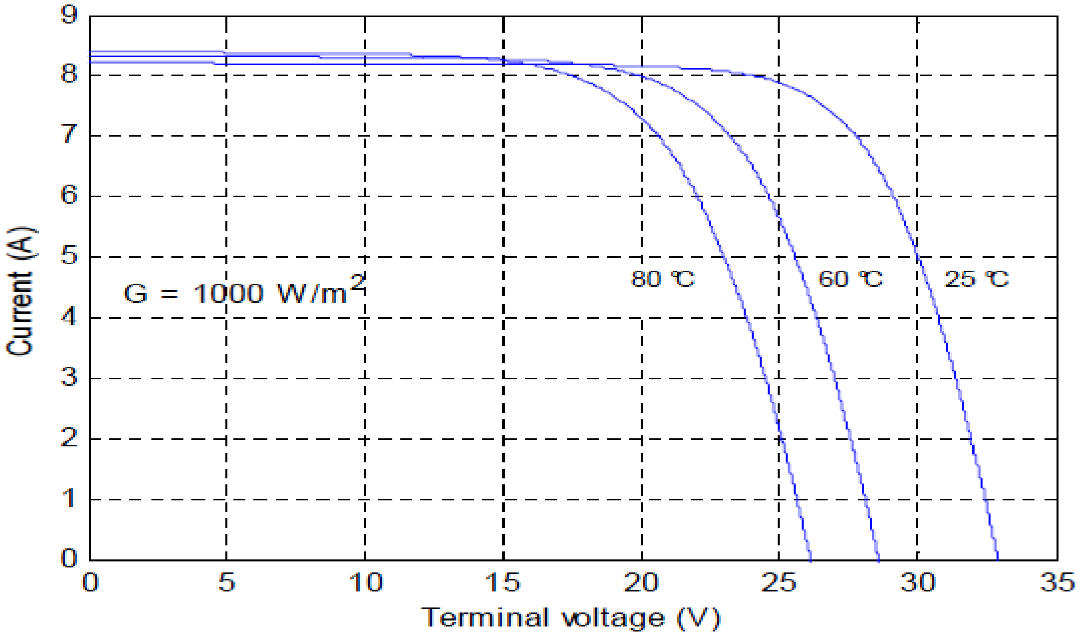

Figure 3.8: I-V characteristics of the PV module at different surface temperatures

3.3 Switched mode DC-DC converters

DC/DC converters are used in a wide variety of applications including power supplies, where the output voltage should be regulated at a constant value from a fluctuating power source, to reduce the ripples in the output voltage or achieve multiple voltage levels from the same input voltage. Several topologies exist to either increase or decrease the input voltage or perform both functions together using a single circuit. The three basic topologies of DC converters are: buck (step down), boost (step up) and the buck-boost converter topologies.

3.3.1 Buck Converter

The schematic diagram of a buck DC converter is shown in figure 3-10. It is composed of two main parts: a DC chopper and an output LC filter to reduce the ripples in the resulting output. If the switch is connected in series with the input DC source then it is called step down chopper or Buck converter. The output voltage of the converter is less than the input as determined by the duration the semiconductor switch Q is closed. Under continuous conduction mode (CCM), the current I_L passing through the inductor does not reach zero. The time integral of the inductor voltage over one period in steady state is equal to zero. From that, the relation between the input and output voltages can be obtained:

$$(V_{in} - V_{out})\,t_{on} - V_{out}t_{off} = 0 \quad (2.1)$$

$$\frac{V_{out}}{V_{in}} = \frac{t_{on}}{t_{on} + t_{off}} = d \quad (2.2)$$

Where D is a Duty cycle.

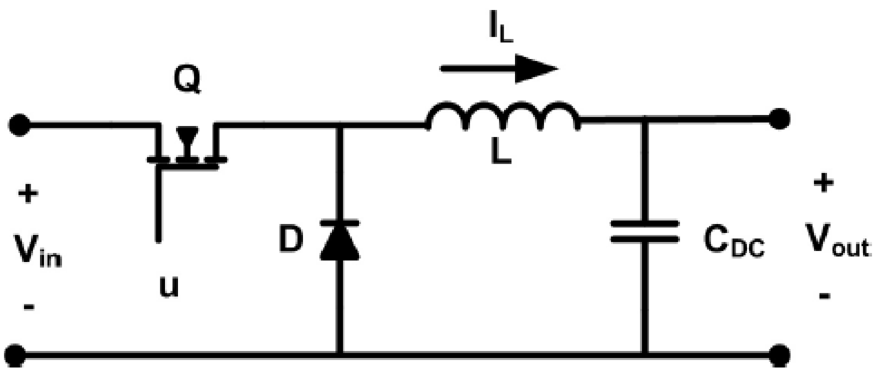

Figure 3.9: DC Buck converter

3.3.2 Boost Converter

The boost DC converter is used to step up the input voltage by storing energy in an inductor for a certain time period, and then uses this energy to boost the input voltage to a higher value. In boost converter or step up chopper the chopper switch is connected in parallel with the input DC source. The circuit diagram for a boost converter is shown in figure 3-11. When switch Q is closed, the input source charges up the inductor while diode D is reverse biased to provide isolation between the input and the output of the converter. When the switch is opened, energy stored in the inductor and the power supply is transferred to the load. The relationship between the input and output voltages is given by:

$$V_{in}t_{on} + (V_{in} - V_{out})\,t_{off} = 0$$

$$\frac{V_{out}}{V_{in}} = \frac{t_{on} + t_{off}}{t_{off}} = \frac{1}{1-d}$$

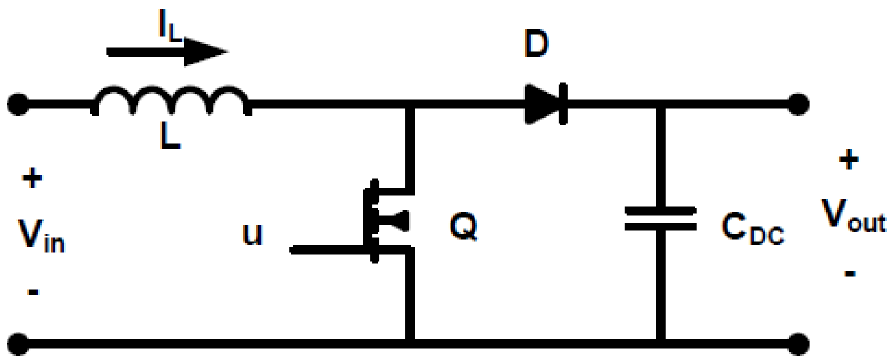

Figure 3.10: Schematic Diagram of DC Boost converter

3.3.3 Buck-Boost Converter

This converter topology can be used to perform both functions of stepping the input voltage up or down, but the polarity of the output voltage is opposite to that of the input. If duty cycle is greater than 0.5 then it functions as a step up chopper and if duty ratio is less than 0.5 then it function as a step down chopper. The input and output voltages of this configuration are related through

$$V_{in}t_{on} + V_{out}t_{off} = 0$$

$$\frac{V_{out}}{V_{in}} = \frac{-t_{on}}{t_{off}} = \frac{-d}{1-d}$$

3.4 Three phase inverters

Voltage source inverters (VSI) are mainly used to convert a constant DC voltage into 3-phase AC voltages with variable magnitude and frequency. Figure 3-12 shows a schematic diagram of a 3 phase VSI. In VSI the output voltage does not depend upon the load conditions whereas the output current depends on load parameters that's why it is called voltage source inverter. The inverter is composed of six switches S_1 through S_6 with each phase output connected to the middle of each "inverter leg". Two switches in each phase are used to construct one leg. The AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output. Pulse width modulation (PWM) techniques are widely used to perform this task. In the simplest form, three reference signals are compared to a high frequency carrier waveform. The result of that comparison in each leg is used to turn the switches ON or OFF. This technique is referred to as sinusoidal pulse width modulation (SPWM). It should be noted that the switches in each leg should be operated interchangeably, in order not to cause a short circuit of the DC supply.

Insulated Gate Bipolar Transistors (IGBTs) and power MOSFET devices can be used to implement the switches. Each device varies in its power ratings and switching speed. IGBTs are well suited for applications that require medium power and switching frequency. But for very high power rating the only option is commutation of SCR which requires forced commutation.

In inverters and choppers main problem is the commutation of silicon controlled rectifier therefore we use devices like IGBT and GTO (gate turn off) in inverters to avoid the commutation problem. In 3 phase VSI we use a large value capacitor in input side in order to make input dc supply constant and also in order to suppress harmonics.

Pulse width modulation(PWM) technique is used to reduce the total harmonics distortion. By increasing the pulses in each half cycle the order of dominant harmonics can be increased which can be easily filtered out with the help of small size filter. Hence by using PWM technique the pulses in each half can be increased in order to increase the order of dominant harmonics and to reduces the harmonics on AC side.

If an inverter supplies power to a magnetic circuit, such as induction motor, then voltage to frequency ratio at the inverter output terminals must be kept constant. This avoids saturation in the magnetic circuit of the device fed by inverters. The various methods for the control of output voltage of inverters are as under:

1. External control of ac output voltage.
2. External control of DC input voltage.
3. Internal control of inverter

The first two methods require the use of peripheral components whereas the third method does not require no peripheral components. Output voltage control from an inverter can also be adjusted by exercising a control within the inverter itself. The most efficient method of doing this by pulse width modulation control within the inverter In this method , a fixed DC input voltage is given to inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most popular method of controlling the output voltage and this method is advantageous because the output voltage control with this method can be obtained without any external components. and with the help of this method lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily and the filtering requirements are minimized. In PWM inverters forced commutation is essential.

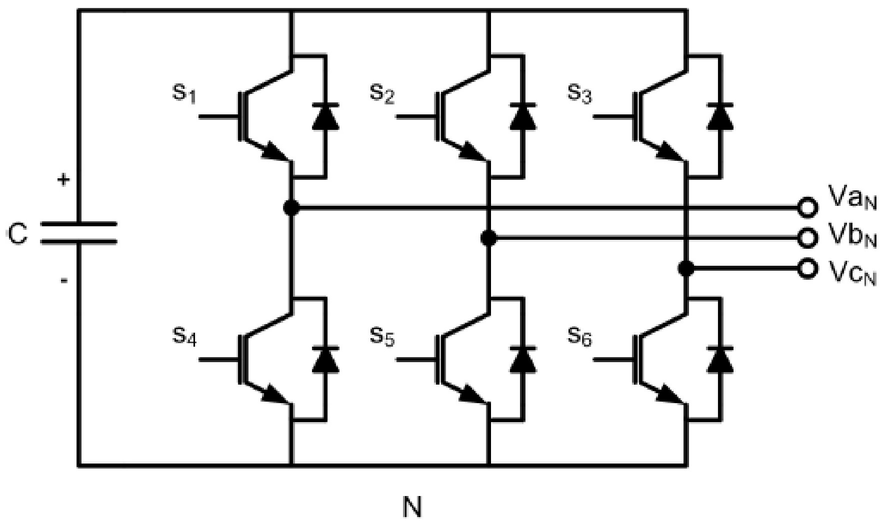

Figure 3.11: Three phase voltage source inverter(VSI)

3.5 .Maximum Power Point Tracking (MPPT) Techniques

MPPT techniques are used to control DC converters in order to extract maximum output power from a PV array under a given weather condition. The DC converter is continuously controlled to operate the array at its maximum power point despite possible changes in the load impedance. Different schemes of MPPT algorithms such as Perturb and Observe, Incremental Conductance, Fractional Open Circuit Voltage, Fractional Short Circuit Current, Fuzzy Logic Control, Neural Network are to be studied and implemented. The MPPT algorithm thus proposed will identify the suitable duty ratio in which the DC/DC converter should be operated to obtain maximum power output. Several techniques have been proposed in literature to perform this task.

3.5.1 Perturb and Observe

The perturb and observe(P&O) algorithm is a simple technique for maximum power point tracking. It is based on controlling the duty cycle (d) of a DC-DC converter to adjust the PV array terminal voltage at the maximum power point. The power output of the array is monitored every cycle and is compared to its value before each perturbation is made. If a change (either positive or negative) in the duty cycle of the DC-DC converter causes output power to increase, the duty cycle is changed in the same direction. If it causes the output power to decrease, then it is reversed to the opposite direction. The algorithm that explains the perturb and observe algorithm is shown in figure3-13.

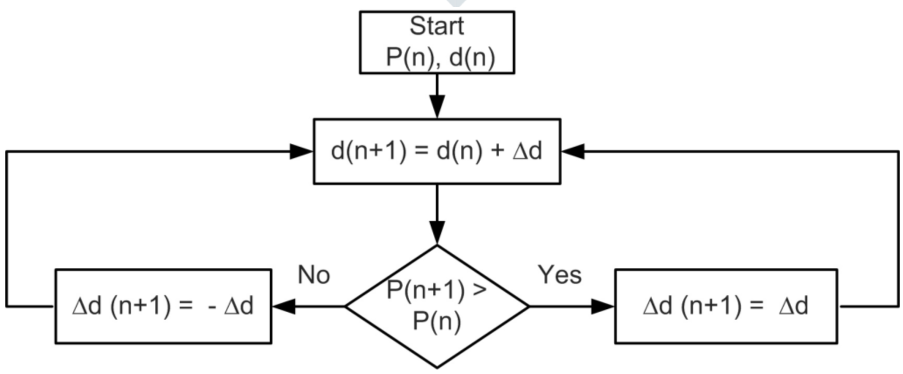

Figure 3.12: Flowchart of the perturb and observe algorithm

The performance of the algorithm is affected by the choice of the perturbation magnitude (Δd) of the converter switching duty cycle. Large perturbations cause large output power fluctuations around the MPP while small perturbations slow down the algorithm. Table 3-1 illustrate the operation sequence of the perturb and observe algorithm.

Table3.1: Perturbation directions for the P&O algorithm based on output power variations

Change in duty cycle, Δd	Effect on output power	Next perturbation, Δd (n+1)
Increase	Increase	Increase
Increase	Decrease	Decrease
Decrease	Increase	Decrease
Decrease	Decrease	Increase

3.5.2 Incremental Conductance

This algorithm exploits the fact that the slope of the power-voltage curve of a PV array is equal to zero at the maximum power point, as shown in figure 3-5. The slope is positive in the area to the left of the maximum power point and negative in the area to the right. Mathematically, this can be summarized as:

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

$$\frac{dP}{dV} > 0 \quad \text{, left of MPP} \qquad (3.3)$$

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

This can be simplified using the following approximation:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + VdI/dV = I + V\Delta I/\Delta V \qquad (3.4)$$

From that (3.3) can be written as :

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

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad \text{, left of MPP} \qquad (3.5)$$

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

The incremental conductance algorithm is illustrated in figure(3.14) given below where V_{ref} is the reference control signal for the DC converter. Similar to the perturb and observe algorithm, the performance of the incremental conductance MPPT is affected by the increment size of V_{ref} used here as a controlled variable. MPPT is a technique that inverters of grid connected PV solar systems employ to maximize power output. In the incremental conductance method the controller measures incremental changes in PV array current and voltage to predict the effect of a voltage change. This method require more computation in the controller but can track changing conditions more rapidly than the perturb and observe method like the P&O algorithm, it can produce oscillations in power output. This method utilizes the incremental conductance of the photovoltaic array to compute the sign of the change in power with respect to voltage(dP/dV).this method of MPPT is faster in comparison to P&O method. The figure below explains the incremental conductance algorithm.

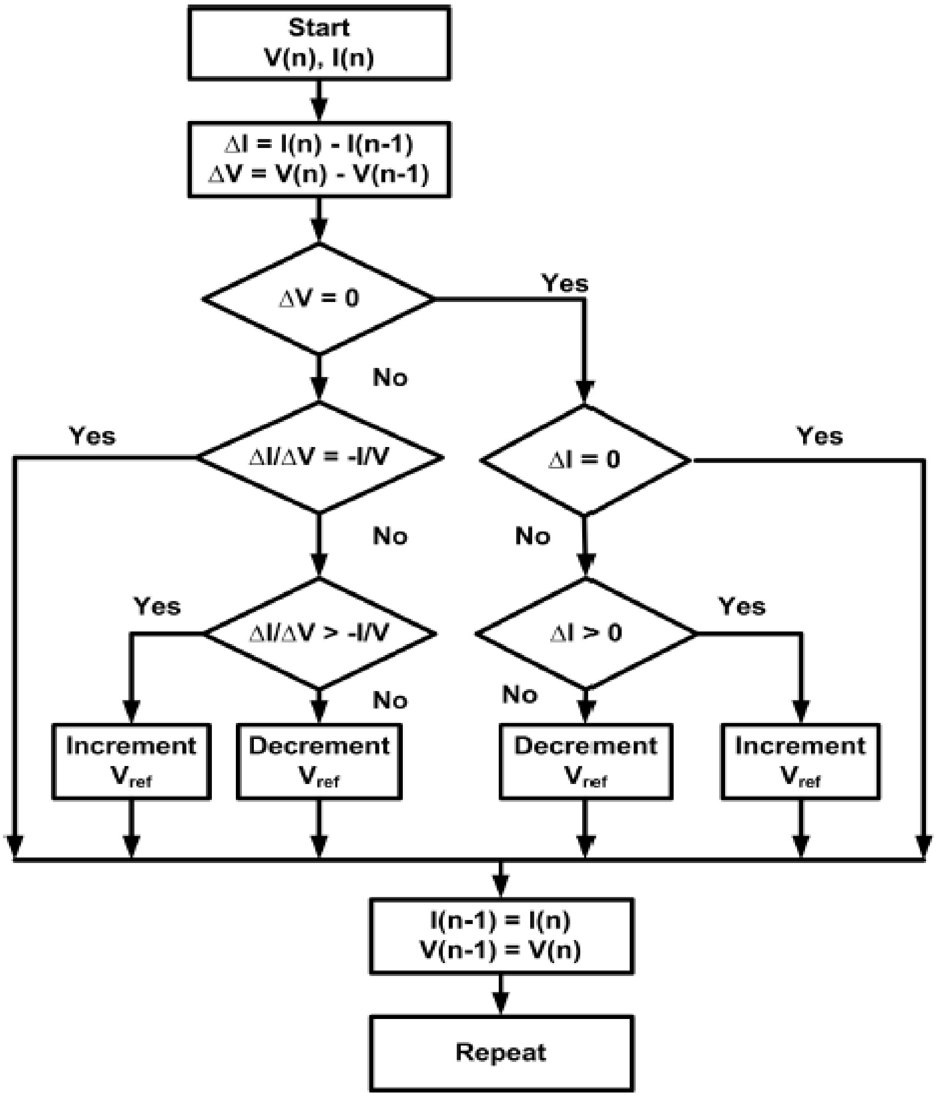

Figure3.13: Flow chart of incremental conductance algorithm

3.5.3 Fractional open circuit voltage

The near linear relationship between VMPP and VOC of the PV array, under varying irradiance and temperature levels, has given rise to the fractional VOC method.

$$VMPP = k1\ Voc$$

where k1 is a constant of proportionality. Since k1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining VMPP and VOC for the specific PV array at different irradiance and temperature levels. The factor k1 has been reported to be between 0.71 and 0.78. Once k1 is known, VMPP can be computed with VOC measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power.

3.5.4 Fractional short circuit current

Fractional ISC results from the fact that, under varying atmospheric conditions, IMPP is approximately linearly related to the ISC of the PV array.

$$IMPP = k2\ Isc$$

where k2 is a proportionality constant. Just like in the fractional VOC technique, k2 has to be determined according to the PV array in use. The constant k2 is generally found to be between 0.78 and 0.92. Measuring ISC during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that ISC can be measured using a current sensor.

3.5.5 Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control popular for MPPT over last decade. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity.

3.5.6 Neural networks

Neural networks based MPPT is one of the techniques suited for implementation using microcontrollers. A neural network is composed of three layers: the input, hidden and output layers. Inputs to a network can be the array terminal voltage and the solar irradiation level or any other measurements needed by the MPPT algorithm. Each node in the network is referred to as a neuron; these neurons are connected together through lines that are associated with certain weighted sums wij. The effectiveness of this MPPT technique is mainly determined by the hidden layer and the amount of training the network received. The training process might span several months or years where the network is subjected to various measurements obtained from the PV system. Using this information, the weights between the neurons are tuned to generate the required output which could be a command to change a DC converter duty cycle. A disadvantage of this technique is the lengthy training process it needs before the neural network can accurately track the maximum power point, in addition to its dependency on the characteristics of the PV array.

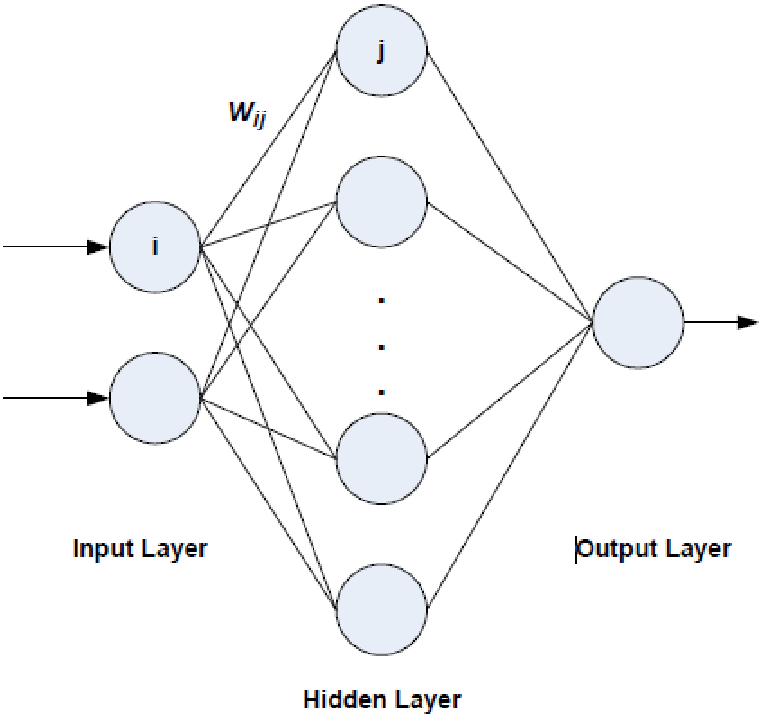

Figure3.14: Neural Network for MPPT control

The neural network is used to identify the optimal operating voltage of the PV system. The controller generates a control signal in real time and the control signal is fed back to the voltage control loop of the inverter to yield the maximum power generation. But in Neural Network method it is observed that even though true MPP was achieved, there is a high level of implementation complexity and the PV array is dependent on the pre-requisite knowledge of PV array characteristics. The relation between the maximum array voltage and insolation is difficult to achieve. The table shown below shows the comparison between various MPPT techniques and with the help of comparison we knows which method gives faster speed of responses and which method have higher accuracy.

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

Table3.2: Characteristics of different MPPT techniques

Different MPPT techniques discussed earlier will suit different applications. For example, in space satellites and orbital stations that involve large amount of money, the costs and complexity of the MPP tracker are not as important as its performance and reliability. The tracker should be able to continuously track the true MPP in minimum amount of time and should not require periodic tuning. In this case, hill climbing/P&O, Incremental Conductance, and Ripple correlation control(RCC) are appropriate. Solar vehicles would mostly require fast convergence to the MPP. Fuzzy logic control, neural network, and RCC are good options in this case. Since the load in solar vehicles consists mainly of batteries, load current or voltage maximization should also be considered. The goal when using PV arrays in residential areas is to minimize the payback time and to do so, it is essential to constantly and quickly track the MPP. Since partial shading (from trees and other buildings) can be an issue, the MPPT should be capable of bypassing multiple local maxima.

CHAPTER 4

CONTROLLING OF THREE PHASE GRID CONNECTED PV SYSTEM

In this chapter the control system is developed in order to operate a grid connected PV system. In starting, the control blocks and its structure of the system are introduced. Then, the function of each and every block is defined. Then an overview of the dq transformation and sinusoidal PWM technique are presented for their importance in building the inverter control system. A PV panel is a non-linear power source, i.e., its output current and voltage (power) depend on the terminal operating point. The maximum power generated by the PV panel changes with the intensity of the solar radiation and the operating temperature. To increase the ratio of output power/cost of the installation, the PV panel should operate in the maximum output power point. The boost DC converter is controlled using an open loop maximum power point tracking technique in order to achieve fast control response to transients and changes in weather conditions. The control system is assessed based on the quality of the injected AC current into the grid, as determined by the Total Harmonic Current Distortion (THDI) limits specified by the IEEE Std. 929-2000; and the speed of the control system in tracking the maximum power point as weather conditions, mainly solar irradiation, change. The system was studied under grid-side fault conditions to examine the effect of the transformer topology selection on the propagation of zero sequence currents to the grid. These currents can intervene with the correct operation of the utility protection relays.

4.1 System structure

A photovoltaic array is used to convert sunlight into DC current. The output of the array is connected to a boost DC converter that is used to perform MPPT functions and increase the array terminal voltage to a higher value so it can be interfaced to the distribution system grid because the distribution grid voltage is quite high. The DC converter controller is used to perform these two functions. A DC link capacitor is used after the DC converter and acts as a temporary power storage device to provide the voltage source inverter with a steady flow of power. The capacitor's voltage is regulated using a DC link controller that balances input and output powers of the capacitor. The voltage source inverter is controlled in the rotating dq frame to inject a controllable three phase AC current into the grid. To achieve unity power factor operation, current is injected in phase with the grid voltage. A phase locked loop (PLL) is used to lock on the grid frequency and provide a stable reference synchronization signal for the inverter control system, which works to minimize the error between the actual injected current and the reference current obtained from the DC link controller. An adjustable speed drive (ASD) and an RL load are connected to the grid to simulate some of the loads that are connected to a distribution system network. An LC low pass filter is connected at the output of the inverter to attenuate high frequency harmonics and prevent them from propagating into the power system grid. A second order LCL filter is obtained if the leakage inductance of the interfacing transformer is referred to the low voltage side. This provides a smooth output current which is low in harmonic content.

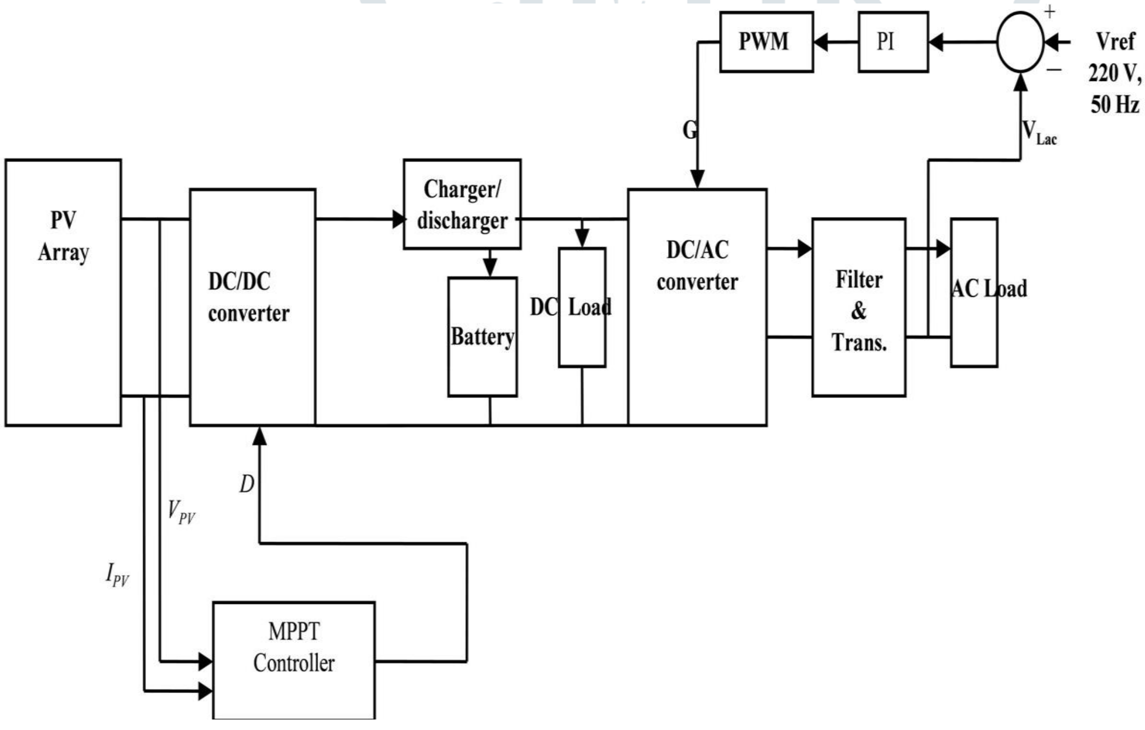

Figure4.1: Grid Connected PV System Structure

4.2 The abc/dq Transformation

The dq transformation is used to transform three phase system quantities like voltages and currents from the synchronous reference frame (abc) to a synchronously rotating reference frame with three constant components when the system is balanced. The relationship that govern the transformation from the abc to dq frame is

$$\begin{bmatrix} x_d \\ x_q \\ x_o \end{bmatrix} = T \times \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (4.1)$$

$$T=\sqrt{\frac{2}{3}}\times\begin{bmatrix}\cos(\omega t) & \cos(\omega t-\frac{2\pi}{3}) & \cos(\omega t+\frac{2\pi}{3})\\ -\sin(\omega t) & -\sin(\omega t-\frac{2\pi}{3}) & -\sin(\omega t+\frac{2\pi}{3})\\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}\end{bmatrix}$$

where x can be either a set of three phase voltages or currents to be transformed, T is the transformation matrix and ω is the angular rotation frequency of the frame . The angle between the direct axis (d-axis) and phase a-axis is defined as θ as shown in figure 4-2.

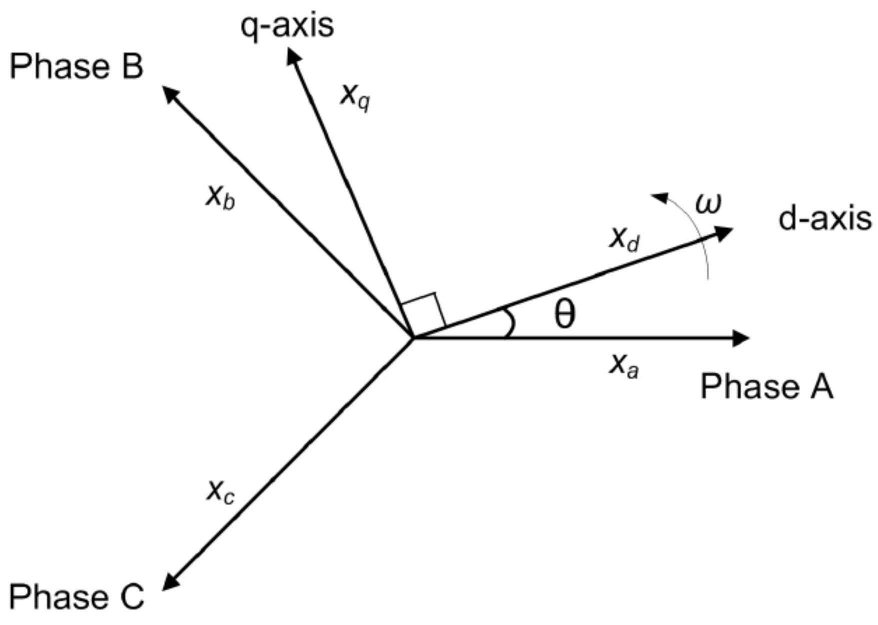

Figure4.2: relationship between the abc and dq reference frames.

The result of this transformation is three constant rotating components: the direct (d), quadrature (q) and zero (0) components. In balanced three phase systems, the zero component can be ignored since

$$x_a + x_b + x_c = 0 \quad (4.2)$$

The inverse transformation from the dq frame to the abc frame can be obtained by applying

$$\begin{bmatrix}x_a\\ x_b\\ x_c\end{bmatrix} = T^{-1}\times\begin{bmatrix}x_d\\ x_q\\ x_o\end{bmatrix} \quad (4.3)$$

$$T^{-1}=\sqrt{\frac{2}{3}}\times\begin{bmatrix}\cos(\omega t) & -\sin(\omega t) & 1/\sqrt{2}\\ \cos(\omega t-\frac{2\pi}{3}) & -\sin(\omega t-\frac{2\pi}{3}) & 1/\sqrt{2}\\ \cos(\omega t+\frac{2\pi}{3}) & -\sin(\omega t+\frac{2\pi}{3}) & 1/\sqrt{2}\end{bmatrix}$$

This transformation is useful in developing the control system for the voltage source inverter under current control to regulate the output of the PV system. Active and reactive powers injected from the PV system can be calculated using the following relationships

$$P=V_d I_{d,injected} + V_q I_{q,injected}$$

$$Q=-V_d I_{q,injected} + V_q I_{d,injected} \quad (4.4)$$

voltages at PCC at the grid side of the transformer, Id,injected and Iq,injected are the dq components of the injected current at the grid side. It is evident that in the computation of reactive power Q, there is cross coupling between the direct and quadrature current and voltage components. This can be eliminated through the use of a phase locked loop (PLL) that locks on the grid frequency in such a way that the quadrature component of the voltage at the point of PV system connection is forced to zero. In this case, equation 4.4 simplifies to

$$P = V_d I_{d,injected}$$
$$Q = -V_d I_{q,injected} \quad (4.5)$$

This means that the direct and quadrature components of the inverter output current can be used to control the active and reactive output powers from the PV array system, as they are related to the injected currents by the transformer turns ratio. This is based on the assumption that the voltage at the point of common coupling (PCC) is relatively constant. In current practice, distribution systems have regulation mechanisms to keep voltage within specified limits.

4.3 Phase Locked Loop (PLL)

The highly increasing penetration of single-phase photovoltaic (PV) systems pushes the grid requirements related to the integration of PV power systems to be updated. These upcoming regulations are expected to direct the grid-connected renewable generators to support the grid operation and stability both under grid faulty conditions and under normal operations. Grid synchronization techniques play an important role in the control of single-phase systems in order to fulfill these demands. Thus, it is necessary to evaluate the behaviors of grid synchronization methods in single phase systems under grid faults. The focus here put on the benchmarking of synchronization techniques, mainly about phase locked loop (PLL) based methods, in single-phase PV power systems operating under grid faults.

The role of the phase locked loop is to provide the rotation frequency, direct and quadrature voltage components at the point of common coupling (PCC) by resolving the grid voltage abc components. Multiple control blocks of the PV system rely on this information to regulate their output command signals. As stated earlier, the PLL computes the rotation frequency of the grid voltage vector by first transforming it to the dq frame, and then force the quadrature component of the voltage to zero to eliminate cross coupling in the active and reactive power terms . A proportional-integral controller is used to perform this task as shown in figure 4-3. The proportional (Kp) and integral (Ki) gains of the controller were set through an iterative process to achieve a fast settling time.

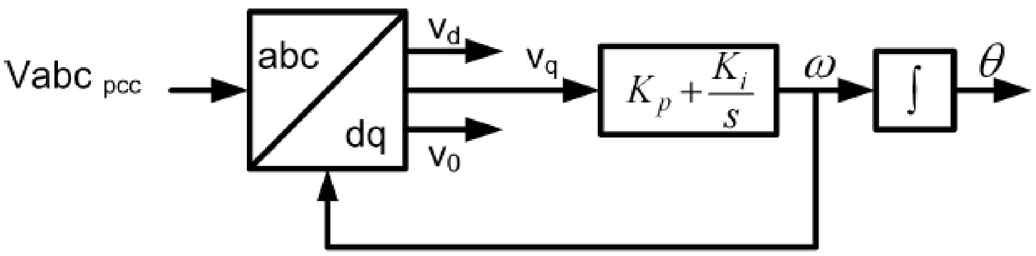

Figure 4.3: Schematic diagram of the phase locked loop (PLL)

The output from the PI controller is the rotation frequency ω in rad/s. Integrating this term results in the rotation angle θ in radians. The operation of the PLL is governed by

$$\omega = K_p V_q + K_I \int V_q \, dt$$
$$\theta = \int \omega \; dt \quad (4.6)$$

4.4 Open loop MPPT using a boost DC converter

Grid connected PV systems are subject to fast dynamics in the power system as opposed to those connected to fixed loads. A fast MPPT technique is needed to help extract power under those conditions. There are several techniques in literature that could quickly locate the maximum power point of a PV array including those based on Fuzzy logic and neural networks. However, they are difficult to implement and depend on the characteristics of the PV system. Perturb and observe and incremental conductance techniques do not suffer from the aforementioned problems, but they have a slower response to weather changes. From that, it is necessary to develop an MPPT technique that is a good compromise between these two types. The open loop MPPT technique used here tries to eliminate the computational overhead associated with the feedback action in present algorithms, without compromising the correct operation of the array. The method proposed here treats the voltage at the maximum power point as a fraction of the PV array open circuit voltage. From several PV cell manufacturers' datasheets, the fraction (Cf) is estimated to be in the range from 0.77 to 0.8. The relationship is dictated by:

$$V_{MP} = C_f \times V_{OC} \qquad (4.7)$$

The determination of the maximum power point in this case requires measuring the array open circuit voltage and multiplying it by a constant. A disconnection of the PV array from the system is needed to obtain that measurement. To get around this difficulty, separate PV cells can be installed within the array and their open circuit voltage can be measured in order to estimate the array voltage. These cells will be subjected to the same solar radiation and surface temperature levels and thus will allow for a very good estimate of VOC. With this concept in mind, the speed of open loop control can be exploited without the need for measuring the output power of the PV array in every control cycle. After finding a value for VMP, the DC-DC boost converter is used to force the array voltage to follow it. This offers improved dynamic and steady state response during the presence of quick variations in the power system or solar radiation level. A separate controller is dedicated for controlling the capacitor voltage to match power going into it from the PV array, and power going out to the grid. The DC converter regulates the PV array voltage by continuously switching on and off at high frequency. The current IL that goes through the inductor in figure 4-4 is the same as the current output of the PV array. When the DC converter switch is turned on, the inductor starts charging and current IL increases. Assuming the voltage drop across the switch is negligible, the PV array voltage is related to the inductor current through the following relationship:

$$V_{PV} = L\frac{dI_L}{dt} \qquad (4.8)$$

As the inductor current reaches steady state, the rate of change of current (dIL/dt) decreases and this causes the PV array terminal voltage to decrease and move down the voltage-power curve as shown in figure 4-4 (a). If the switch is closed long enough, the PV array voltage will eventually drop to zero and the inductor will have the PV array short circuit current passing through it.

When the switch is turned off, the inductor and the PV array will start supplying current to the DC link capacitor. This causes the inductor to discharge and its current decreases with time. The direction along the PV array voltage-power curve is reversed and voltage will start moving towards VOC as shown in figure 4-4 (b). By quickly switching the DC converter on and off around the maximum power point, the PV array will output maximum power at a given solar irradiation and temperature levels. The switching function that governs the DC converter operation is:

$$u = \begin{cases} 1, & V_{PV} - V_{mp} > 0 \\ 0, & V_{PV} - V_{mp} < 0 \end{cases} \qquad (4.9)$$

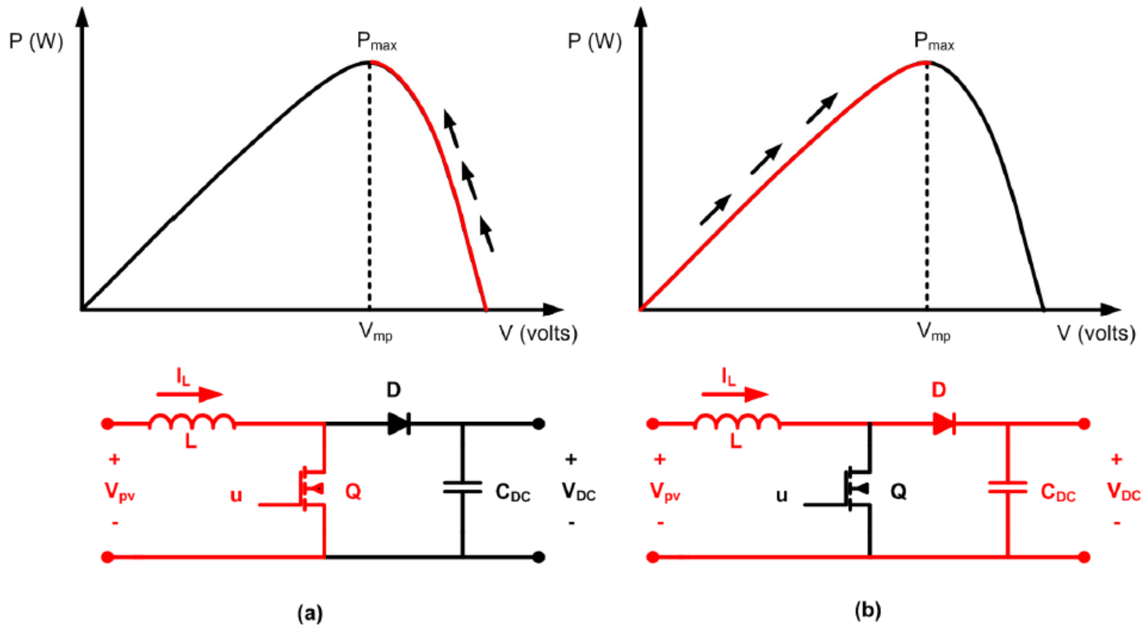

Figure 4.4: Output power from the PV array when the converter switch is (a) ON and (b) OFF

The PV array voltage will slide along the curve following the direction dictated by the switching signal. Implementation of the switching function can be achieved using a comparator circuit that triggers when the instantaneous PV array voltage exceeds the maximum power point. After the DC converter switch turns on, the array operating voltage will move back to the maximum power point as in figure 4-4 (a). If the PV array voltage drops below the maximum power point, the switch is turned off to allow the inductor to discharge power to the DC link capacitor and allow the array voltage to return to the MPP as in figure 4-4 (b). A simple comparator circuit can be realized using an op amp as shown in figure 4-5.

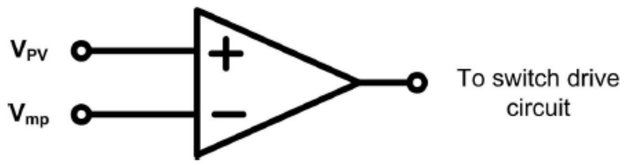

Figure 4.5: comparator circuit

4.5 Modeling and Control of the Three phase VSI in the dq frame

The state equations describing the dynamics of the output currents and voltages of the voltage source inverter are derived in this section. The time derivatives of the inverter output current and voltage are

$$L_f \frac{d}{dt} I_{inv} = V_{inv} - V_C \quad (4.10)$$

$$C_f \frac{d}{dt} V_C = I_{inv} - I_G \quad (4.11)$$

where Lf and Cf are the filter’s inductance and capacitance respectively, Vc is the capacitor voltage and IG is the current injected into the grid as shown in figure 4-6. Equations 4.10 and 4.11 are in matrix format where

$$L_{inv} = [I_{inv,a} \quad I_{inv,b} \quad I_{inv,c}]^T,$$

The above equation explains how we get the inverse of inductance matrix.

$$V_C = [V_{Ca} \quad V_{Cb} \quad V_{Cc}]^T$$

The above equation explains how we get the matrix that explains the capacitance voltage. The next equation explains the matrix related to filter inductance and filter capacitance.

$$L_f = \begin{bmatrix} L_f & 0 & 0 \\ 0 & L_f & 0 \\ 0 & 0 & L_f \end{bmatrix}, \ C_f = \begin{bmatrix} C_f & 0 & 0 \\ 0 & C_f & 0 \\ 0 & 0 & C_f \end{bmatrix} \qquad (4.12)$$

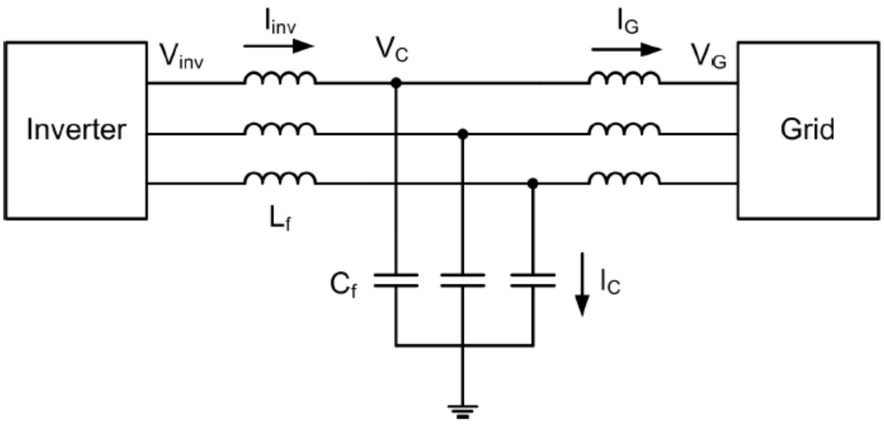

Figure 4.6: circuit diagram of a three phase grid connected inverter

Multiplying both sides of equation 4.10 by the transformation matrix T in 4.1, the VSI model in the dq frame can be obtained . The following procedure is adopted to find the result of the transformation

$$\mathrm{T}L_f \frac{d}{dt} I_{abc} = T(V_{inv} - V_c)$$

$$\mathrm{T}L_f \frac{d}{dt} T^{-1} \widehat{I_{inv}} = T(V_{inv} - V_c) \qquad (4.13)$$

$$\mathrm{T}L_f \widehat{I_{inv}} \frac{d}{dt} T^{-1} + \mathrm{T}L_f T^{-1} \frac{d}{dt} \widehat{I_{inv}} = \widehat{V_{inv}} - \widehat{V_C}$$

where (^) is used to denote dq quantities. The previous steps use the relationship governing the inverse transformation, which is

$$I_{abc} = T^{-1} I_{dqo} \qquad (4.14)$$

As a result which is given in equation 4.10 becomes

$$\begin{bmatrix} 0 & \omega L_f & 0 \\ -\omega L_f & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \widehat{I_{inv}} + L_f \frac{d}{dt} \widehat{I_{inv}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} (\widehat{V_{inv}} - \widehat{V_C}) \qquad (4.15)$$

Since the 0-component is not contributing to both sides of the equation, it can be omitted and 4.15 can be written as

$$\begin{bmatrix} \dot{I}_{inv,d} \\ \dot{I}_{inv,q} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} I_{inv,d} \\ I_{inv,q} \end{bmatrix} + \begin{bmatrix} 1/L_f & 0 \\ 0 & 1/L_f \end{bmatrix} \begin{bmatrix} V_{inv,d} \\ V_{inv,q} \end{bmatrix} - \begin{bmatrix} 1/L_f & 0 \\ 0 & 1/L_f \end{bmatrix} \begin{bmatrix} V_{Cd} \\ V_{Cq} \end{bmatrix} \qquad (4.16)$$

This represents the state equation of the inverter output current in the dq frame. Applying the same procedure on 4.11, the state equation for the capacitor voltage is

$$\begin{bmatrix} \dot{V}_{Cd} \\ \dot{V}_{Cq} \end{bmatrix} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \begin{bmatrix} V_{Cd} \\ V_{Cq} \end{bmatrix} + \begin{bmatrix} 1/C_f & 0 \\ 0 & 1/C_f \end{bmatrix} \begin{bmatrix} I_{Ld} \\ I_{Lq} \end{bmatrix} - \begin{bmatrix} 1/C_f & 0 \\ 0 & 1/C_f \end{bmatrix} \begin{bmatrix} I_{Gd} \\ I_{Gq} \end{bmatrix} \quad (4.17)$$

The output current from the VSI is regulated using proportional-integral controllers to force the error signal in each dq-component to zero. The error signal is defined as the difference between the measured output current and the reference current. The following control laws generate the required command voltages at the inverter output such that the error in the output current is minimized

$$v_d^* = k_p(I_d^* - I_d) + k_I \oint (I_d^* - I_d)\, dt - \omega L_f I_q + V_{Gd}$$

(4.18)

$$v_q^* = k_p(I_q^* - I_q) + k_I \oint (I_q^* - I_q)\, dt - \omega L_f I_d + V_{Gq}$$

Where I_d^* and I_q^* are the dq reference currents, VGd and VGq are the dq voltages at the point of common coupling. The command voltages, v_d^* and v_q^*, are transformed back to the natural frame to be sent to the sinusoidal PWM block to generate the switching signals for the inverter. Under unity power factor operation, the PV system injects real power only into the grid. In that case, reactive power injection is forced to zero by setting the reference current I_q^* to zero according to (4.5). The real power injection is controlled by I_d^* which is extracted from the power mismatch of the DC link capacitor. The capacitor voltage changes according to the following relation

$$\frac{d}{dt} V_{DC}^2 = \frac{2}{C}(P_{in} - P_{out}) \quad (4.19)$$

where Pin is the input power to the capacitor coming from the DC converter, Pout is the output power going to the inverter and then to the grid ignoring power losses, and C is the capacitance of the DC link. To keep the voltage constant, it is necessary to balance Pin and Pout. Since the input power is controlled by the DC converter to be the maximum output power from the PV array, the control system of the inverter performs the task of controlling the real output power by controlling I_d^*. This is achieved by using a separate DC link voltage PI controller using

$$I_d^* = \frac{1}{V_{Gd}}\left(k_P(P_{in} - P_{out}) + K_I \int (P_{in} - P_{out})\, dt\right) \quad (4.20)$$

A schematic diagram of the controller is shown in figure 4-7 below. It accepts the power mismatch of the DC link capacitor as an input, and uses a proportional integral controller to generate a power control signal necessary to drive the mismatch to zero. The power control signal is then divided by the direct component of the grid voltage to obtain the reference current I_d^*. This reference is sent to the current controllers to regulate the output current of the inverter. The PI controller had a low bandwidth due to slow variations in the DC link power and to ensure that the reference current signal does not suffer any abrupt changes.

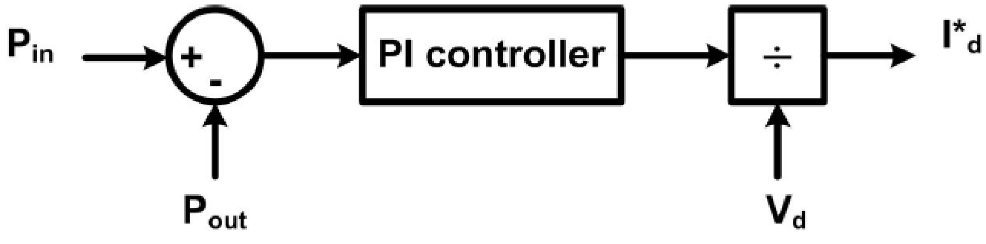

Figure 4.7: Schematic diagram of the DC link controller

4.6 Sinusoidal Pulse Width Modulation (SPWM)

The sinusoidal pulse width modulation technique is used to control the voltage source inverter by producing the gating signals for the semiconductor switches. This technique is used to obtain three phase output voltages that can be controlled in magnitude and frequency. A reference or modulating signal is compared to a high frequency carrier signal; the result of this comparison in each phase is used to activate the switches accordingly. A separate modulating signal is used for each phase with a phase shift of 120° between them as shown in figure 4-8.

In sinusoidal pulse width modulation the pulse width is increased at 90° and reducing pulse width at other positions. Two important quantities in SPWM are the amplitude and frequency modulation indices, ma and mf respectively. The amplitude modulation index, ma, is defined as the ratio between the amplitude of the modulating signal to the carrier signal, while the frequency modulation index, mf, is the ratio between the frequency of the carrier signal to that of the modulating signal in 4.21 on the next page.

$$m_a = \frac{V_m}{V_{carrier}}$$
$$m_f = \frac{f_{carrier}}{f_m} \qquad (4.21)$$

When the amplitude of the modulating signal is greater than that of the carrier signal, the upper switch in the corresponding phase leg is activated. This leads to the output voltage having the same magnitude of the DC link voltage. The switches in each phase leg operate in a complementary fashion in order to avoid shorting the DC kink capacitor. Figure 4-8 shows the modulating signals for a three-phase inverter and phases A and B output voltages. The line voltage between these two phases is obtained by subtracting Vb from Va. It is clear that the output voltages need to be filtered to obtain clean sinusoidal voltages. The harmonic content in the output voltages of the inverter depends on the choice of the frequency of the carrier signal. Any even harmonics in the output line voltages in addition to harmonic orders below mf – 2 will be eliminated if the following conditions hold

$$m_f > 9$$
$$m_f = odd\ multilples\ of\ 3 \qquad (4.22)$$

In addition to that, harmonics will be centered at mf and its multiples 2 mf, 3 mf …etc., which helps ease the filtering requirements determined by the cutoff frequency. A possible choice is to have mf =99 which means that

$$f_{carrier} = 99 \times f_m = 99 \times 50 = 4950\ Hz$$

The magnitude of the output phase voltage (rms) can be determined using

$$V_{rms} = m_a \frac{V_{DC}}{2\sqrt{2}} \qquad (4.23)$$

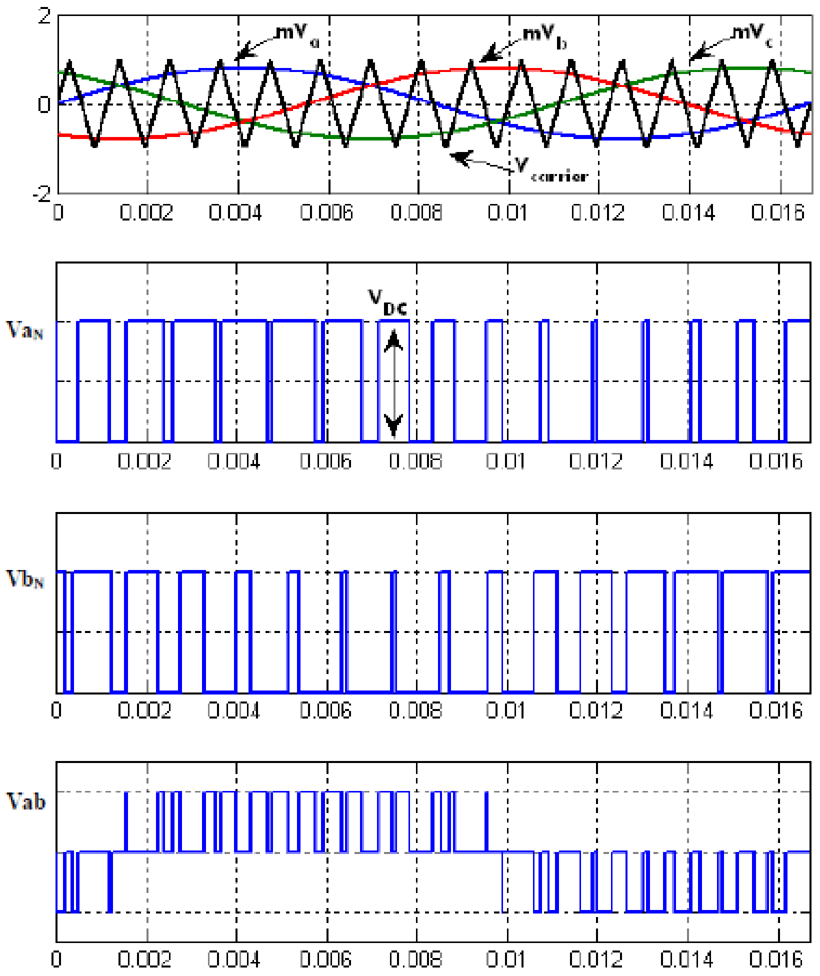

Figure 4.8: SPWM modulation signals for the VSI

4.7 Behavior of the system during fault conditions

The operation of the distribution system protection devices can be disrupted when distributed generation (DG) sources are connected. Protection relays in radial distribution systems are set to respond to a certain magnitude of fault current, which is determined by the short circuit level at the fault location. If a DG source happens to be located between a distribution sub-station and a fault, it can contribute to the fault current. If the fault current contribution from the grid decreases, the protection relay may not be able to detect the fault and a "relay under reach" situation occurs. The situation is depicted in figure 4-9. Most utilities require DG sources to disconnect within a few cycles of detecting a fault in the system. That might be difficult to implement especially when DG sources comprise a major part of the generated power. In Denmark for example, about 20% of the country's total electricity supply in 2007 was generated from renewable energy sources like wind turbines. It is important to understand the behavior of DG sources during fault conditions and how they interact with the power system.

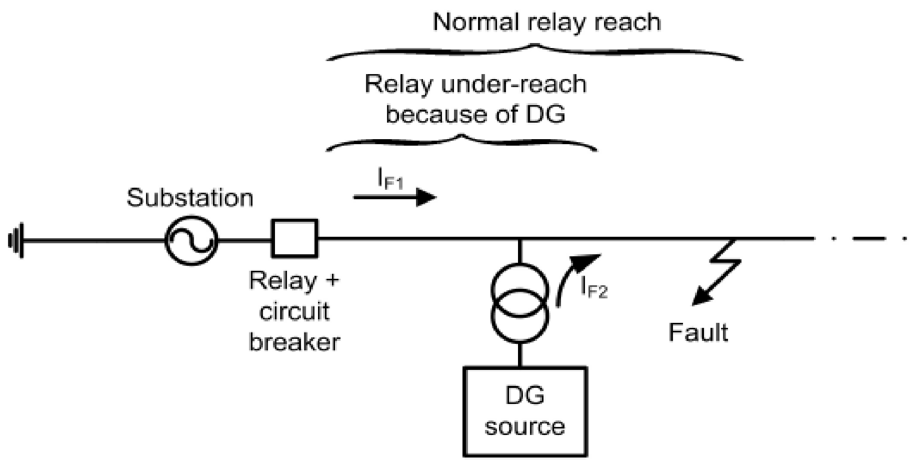

Figure 4.9: Relay under reach because of a DG source

Inverter based DG units including PV arrays do not contribute significant fault current to the system because of the presence of current limiting protection implemented in the inverter controls. This is important not to overload the power electronic switches beyond their ratings. However, the interfacing transformer between the array and the grid can play a role in the propagation of zero sequence current back to the grid. Fault current can circulate through the transformer grounding point and interact with other non-faulty phases. A simulation study was conducted in order to examine the system under these conditions. it is expected that the future grid-connected single-phase PV systems can not only maintain the stability and quality of the grid, but also have some ancillary functions, such as reactive power support and fault ride through (FRT) capability. In that case, the grid monitoring and synchronization techniques and the control strategies should be ready for single-phase PV applications common coupling . For instance, it is recommended in IEEE Standard 1547 that the low-voltage systems should cease to energize when the grid voltage is lower than 0.85 p.u or higher than 1.1 p.u.

CHAPTER- 5

RESULTS AND CONCLUSIONS

The optimum PV array and inverter sizes for a grid connected PV system have been obtained for defined load .The losses have been decreased by different combinations of strings, modules and also the inverter capacity. The detailed losses have been explained.
For the renewable energy system particularly For the solar energy system the major factor in decreasing the cost and optimally sizing the system. Various methods are being utilized by different organizations in planning and sizing the grid-connected PV systems. In this project optimal size of PV, inverter of a grid-connected PV system has been used and investigated.

SL NO	SET: 1	VOLTAGE	CURRENT(ma)	POWER(WATTS)
1	Irradiance: 1000 watt/m^2	0	2.585(Isc)	0
2	Temp: 25C	5	2.583	12.91
3		10	2.532	25.37
4		15(Voc)	2.253	36.46 (Pmax)
1	Irradiance: 1000 watt/m^2	0	2.542(Isc)	0
2	Temp: 50C	5	2.542	12.71
3		10	2.532	25.32
4		15(Voc)	2.2	33.8 (Pmax)
1	Irradiance: 1000 watt/m^2	0	2.5(Isc)	0
2	Temp: 75C	5	2.5	12.91
3		10	2.498	25.37
4		15(Voc) O	2.432	23.95 (Pmax)

SL NO	SET: 2	VOLTAGE	CURRENT(ma)	POWER(WATTS)
1	Irradiance: 200 watt/m^2	0	0.5(Isc)	0
2	Temp: 25C	5	0.5	2.5
3		10	0.4984	4.984
4		15(Voc)	0.4412	6.618(Pmax)
1	Irradiance: 600 watt/m^2	0	1.525(Isc)	0
2	Temp: 50C	5	1.525	7.626
3		10	1.516	15.16
4		15(Voc)	1.255	18.82 (Pmax)
1	Irradiance: 1000 watt/m^2	0	2.585(Isc)	0
2	Temp: 75C	5	2.583	12.91
3		10	2.537	25.37(Pmax)
4		15(Voc) O	1.597	23.95

SL NO	SET: 3	VOLTAGE	CURRENT(ma)	POWER(WATTS)
1	Irradiance: 200 watt/m^2	0	0.5(Isc)	0
2	Temp: 25C	5	0.5	2.5
3		10	0.4984	4.984
4		15(Voc)	0.4412	6.618(Pmax)
1	Irradiance: 600 watt/m^2	0	1.5(Isc)	0
2	Temp: 25C	5	1.5	7.5
3		10	1.498	14.98
4		15(Voc)	1.437	21.55 (Pmax)
1	Irradiance: 1000 watt/m^2	0	2.5(Isc)	0
2	Temp: 25C	5	2.5	12.91
3		10	2.498	25.37(Pmax)
4		15 O	2.432	23.95
5		20(Voc)	.3575	7.15

COMPARATIVE STUDY OF SOLAR CELL W.R.T FILL FACTOR

SL NO	IRRADIANCE(Watt/m^2)	Voc	Isc	Pmax	FILL FACTOR
1	200	15	0.5	6.618	0.88
2	600	15	1.5	21.55	0.95
3	1000	20	1.2	25.37	1.05

Pmax=FF*Voc*Isc.

Fill factor

The fill factor is denoted as FF, is a parameter that helps in characterizing the non- linear electrical nature of the solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc, and it gives an idea about the power that a cell can produce with an optimal load under given conditions, P=FF*Voc*Isc. Fill factor is also an indicator of quality of cell. With FF approaching towards unity the quality of cell gets better. Fill Factor can be improved in many ways.

CONCLUSIONS

In this mathematical model of a 70W photovoltaic panel has been developed using MATLAB Simulink. This model is used for the maximum power point tracking algorithms. The P&O and Incremental conductance MPPT algorithms are discussed and their simulation results are presented. It is proved that Incremental conductance method has better performance than P&O algorithm. These algorithms improve the dynamics and steady state performance of the photovoltaic system as well as it improves the efficiency of the BUCK BOOST converter system.

Photovoltaic Systems have developed into a mature technology used for mainstream electricity generation. Reactive power support with regards to varying load power factor and varying PV penetration levels has been studied. Anti-islanding function of the PV system has been studied and found that the critical islanding time of the PV system for the system considered is 125ms. Further, the Performance Ratio of a typical grid connected system in India is calculated in order to compare the performance of the PV system with other systems throughout the world. The studies carried out will help PV power generators and utilities the issues to be studied for a grid connected PV system.

FUTURE SCOPE

Improvement to this project can be made by tracking the maximum power point in changing environmental conditions. Environmental change can be change in solar irradiation or change in ambient temperature or even both. This can be done by using Simulink models to carry out MPPT instead of writing it code in Embedded MATLAB functions. In the Simulink models the solar irradiation and the temperature can be given as variable inputs instead of constant values as done here

LIST OF FIGURES

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