Reactive Power Control in Grid Connected Photovoltaic System

A Dissertation submitted in the partial fulfillment of the requirements for the Degree of

Master of Engineering

in

Power Systems

Submitted by

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Punjab (India)

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DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, **"Reactive Power Control in Grid Connected Photovoltaic System"** in the partial fulfillment of the requirement for the award of the Degree of **Master of Engineering** in **Power Systems**, submitted to **Electrical & Instrumentation Engineering Department** of **Thapar Institute of Engineering & Technology, Patiala**, is an authentic record of my own work carried under the supervision of **Dr. Sanjay K. Jain**. It refers other researcher's work which is duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part or in full to any other university except as reported in the text and references.

Place: Patiala
Date: 29-06-2018

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This is to certify that the above statement made by the candidate is correct and true to best of our knowledge.

Date: 29.06.2018

Dr. Sanjay K. Jain
Associate Professor

Abstract

An ever increasing population, modernization and industrialization has led to the increase of energy requirement in all sectors of economy. Fossil fuels have been the most important source of energy from many years but they are finite and will deplete in coming years. They are non-renewable and cause global carbon emissions which is an important environmental concern in the present scenario. Among all the available renewable sources, solar energy is used widely because it is clean, noise free and the photovoltaic (PV) system can be installed easily to convert the solar energy into electricity. PV system can work in standalone mode as well in grid connected mode. During the dissertation work, a PV system connected to grid has been modeled with the help of MATLAB/Simulink in which Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) technique is used to make the system operate at maximum power point and hence constant output voltage of DC-DC boost converter is observed. Power generated by PV array has to be fed to the grid but the output voltage of PV array is DC which is converted to AC with the help of voltage source inverter (VSI) and is then fed to the grid. In order to manage the flow of reactive power in the system and switching pattern of voltage source inverter, synchronous reference frame (SRF) theory is implemented which is a d-q control based on conversion of abc currents involving algebraic equations. The complete grid connected PV system is analyzed for different values of load and reactive power compensation is investigated in this work.

Keywords: Photovoltaic (PV) system, Perturb and Observe (P&O), Maximum power point tracking (MPPT) technique, Voltage source inverter (VSI), Synchronous reference frame (SRF) theory

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List of Abbreviations

PV	Photo Voltaic
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MNRE	Ministry of New & Renewable Energy
MPPT	Maximum Power Point Tracking
VSI	Voltage Source Inverter
DC	Direct Current
AC	Alternating Current
P&O	Perturb and Observe
INC	Incremental Conductance
PLL	Phase Locked Loop
PI	Proportional Integral
PWM	Pulse Width Modulation
SRF	Synchronous Reference Frame
DSTATCOM	Distribution Static Compensator
VSC	Voltage Source Converter
NREL	National Renewable Energy Lab
SPWM	Sinusodial Pulse Width Modulation
MPP	Maximum Power Point
PCC	Point of Common Coupling
THD	Total Harmonic Distortion

Chapter 1

Introduction

1.1 Motivation

The demand for clean, economical and renewable energy has increased consistently over the past few decades due to increase in level of carbon dioxide emissions and depleting fossil fuels which is a serious concern. Among various available renewable resources, solar is the most commonly preferred due its availability in abundance and environment friendly conversion to electricity through photovoltaic (PV) process. Increase of interest in PV systems has resulted into research and many development activities. The production and forecast of fossil fuels is shown in Figure 1.1 [1].

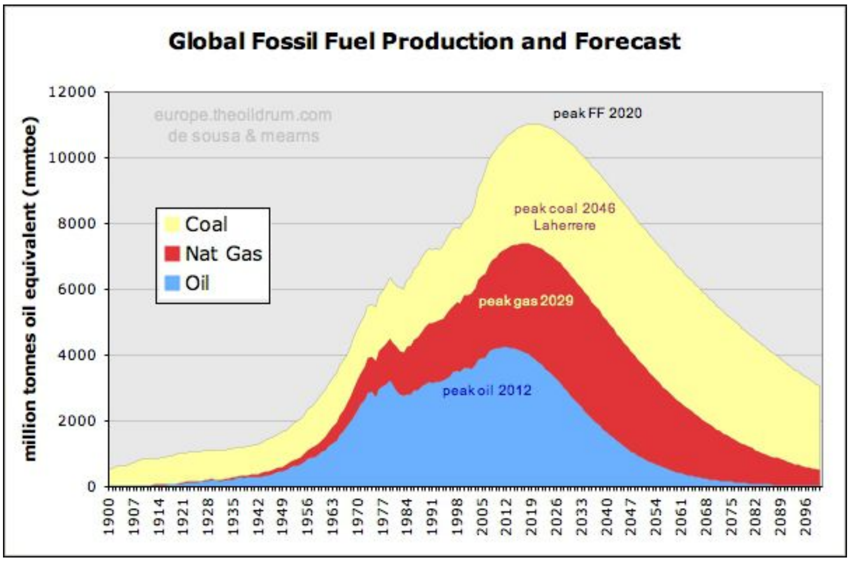

Figure 1.1: Fossil fuel production and forecast

It is clearly indicated that by 2096 fossil fuels will almost deplete. To tackle the problem of shortage of conventional energy sources, alternate sources of energy are being explored and development of various technologies is going on to bring these resources into the main stream sources so that they can compete with traditional resources in quantity and quality. PV is among the fastest growing industries and will contribute in the global electricity production in the future. As per the Paris Agreement held on 20 April, 2018 which aims to deal with greenhouse gas emissions mitigation and to decrease global average temperature, it has become the need of the hour to shift from conventional sources of energy to alternate ones.

Worldwide growth of solar potential

According to International Energy Agency (IEA), year 2016 was witnessed as the year in which solar PV addition rose faster for the first time than any other fuel as shown in Figure 1.2 [2]. The actual growth in different energy sources is

Wind Capacity growth in 2017-2022 is 329 GW

Solar Capacity growth in 2017-2022 is 438 GW

Hydropower Capacity growth in 2017-2022 is 119 GW

Others Capacity growth in 2017-2022 is 44 GW

%age growth from wind and solar alone is 82%.

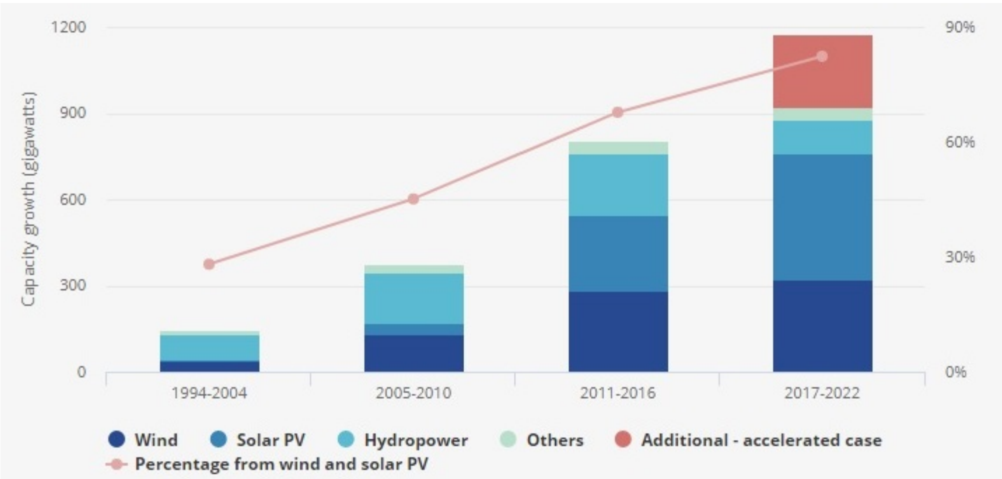

Figure 1.2: Renewable electricity capacity growth by technology

According to International Renewable Energy Agency (IRENA), the different forms of renewable energy will witness huge growth in coming years which will create employment opportunities in this sector. According to the Figure 1.2 [5] it is clear that due to easy installation and abundance of sunlight, PV will contribute maximum in the production of electricity among all renewable energy sources. If growth is there in any sector it is clear that employment rate in that particular sector will boost up. The jobs in renewable energy will increase among which maximum jobs will be created in solar energy as shown in Figure 1.3 [5].

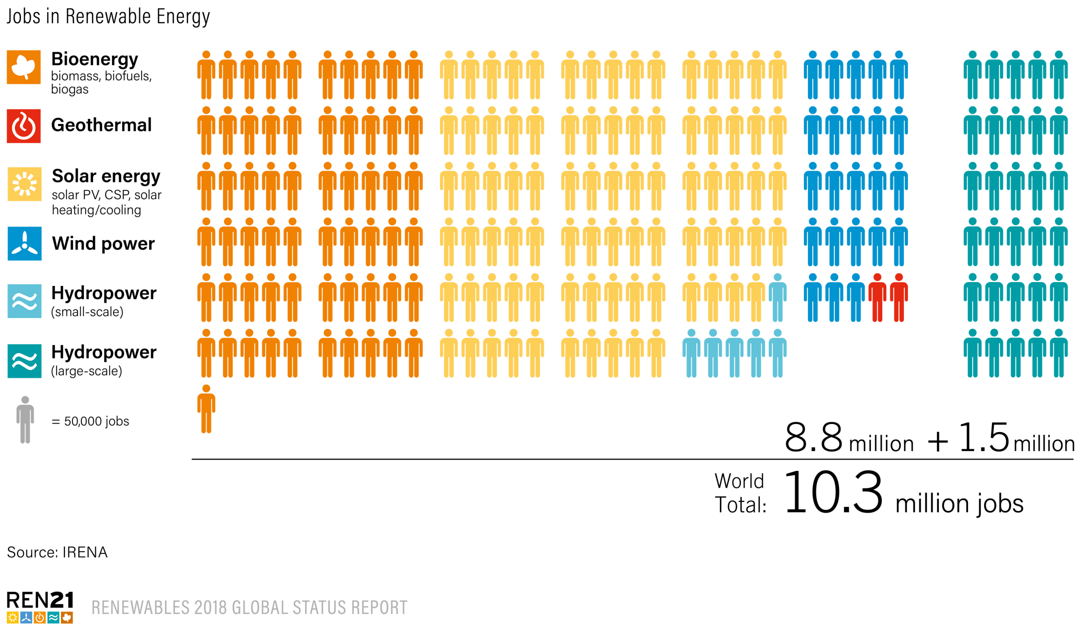

Figure 1.3: Growth of employment in renewable energy

The potential of renewable energy sources is though utilized in different sectors but production of electricity or power sector will see maximum growth as per the prediction by IEA as shown in Figure 1.4 [2].

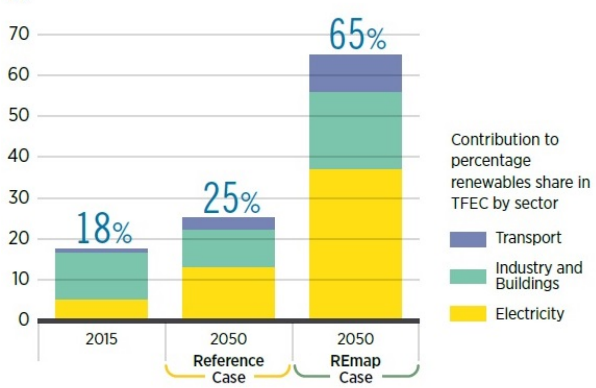

Figure 1.4: Contribution of renewable in Total Final Energy Consumption by 2050

Growth of solar potential as per Indian scenario

India is located in such a strategic geographical location that the country experiences sunny weather for 250 to 300 days in a year. According to World Bank, India is one such country among the countries which have best conditions to capture and use solar energy. Vast potential of India in the field of solar energy should be utilized properly in order to sustain economic growth and make India energy surplus. There are many states which receive good amount of sunlight with Rajasthan and Northern Gujrat having the highest annual radiation. Figure 1.5 [6] describes the growth of different sources of energy from 1985 to 2017. As clear from the trend shown it can be concluded that growth of renewable energy sources can be seen in recent years.

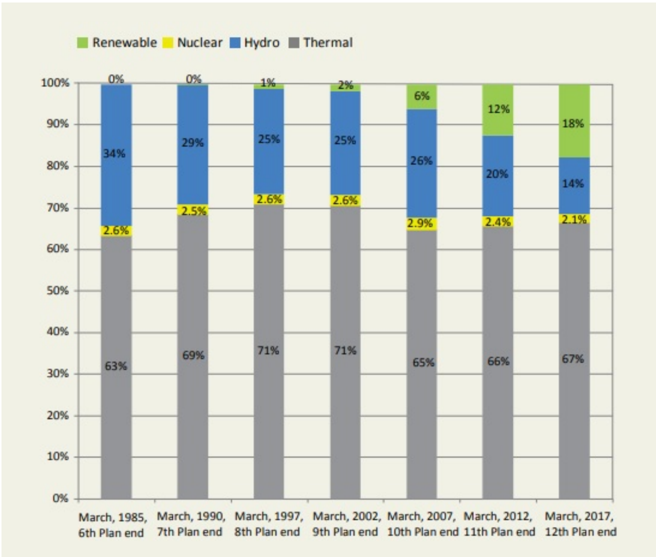

Figure 1.5: %age increase in various sources of energy from 1985-2017

Various initiatives taken by Government of India to enhance the optimum use of solar potential

The effort of the country is visible from the fact that it has a ministry dedicated to renewable resources Ministry of New & Renewable Energy (MNRE) which works in collaboration with different nodal agencies of each state to set up highly efficient solar power plants and take some appropriate steps to convince the citizens to enhance the use the solar energy. Some of the steps taken by the government are listed below:

- To accomplish the target of 175 GW of renewable energy by 2022 out of which 100 GW is set for solar energy. Out of 100 GW, 40 W is for rooftop and remaining 60 GW through grid connected solar projects. To achieve this target various schemes have been introduced that are implemented by central and state government at regular intervals.

- India took an initiative in June 2014 and suggested to form a group of nations lying in Tropic of Cancer and Tropic of Capricorn. MNRE with the help of Ministry of External Affairs started working on this goal to increase promotion and utilization of solar energy. On 14 May, 2015 International Source Alliance (ISA) was given green flag at National Institute of Solar Energy of having 121 member nations.

- Some major amendments in national tariff policy have been made to promote the usage of PV system at commercial and residential level.

- With the financial support of Rs 81 billion government of India has passed the development of 40,000 MW infrastructure of solar parks by 2020. The work in 8 solar parks have already been started that make up 8900 MW of total capacity. The states with maximum potential for solar energy are shown in Figure 1.6 [6].

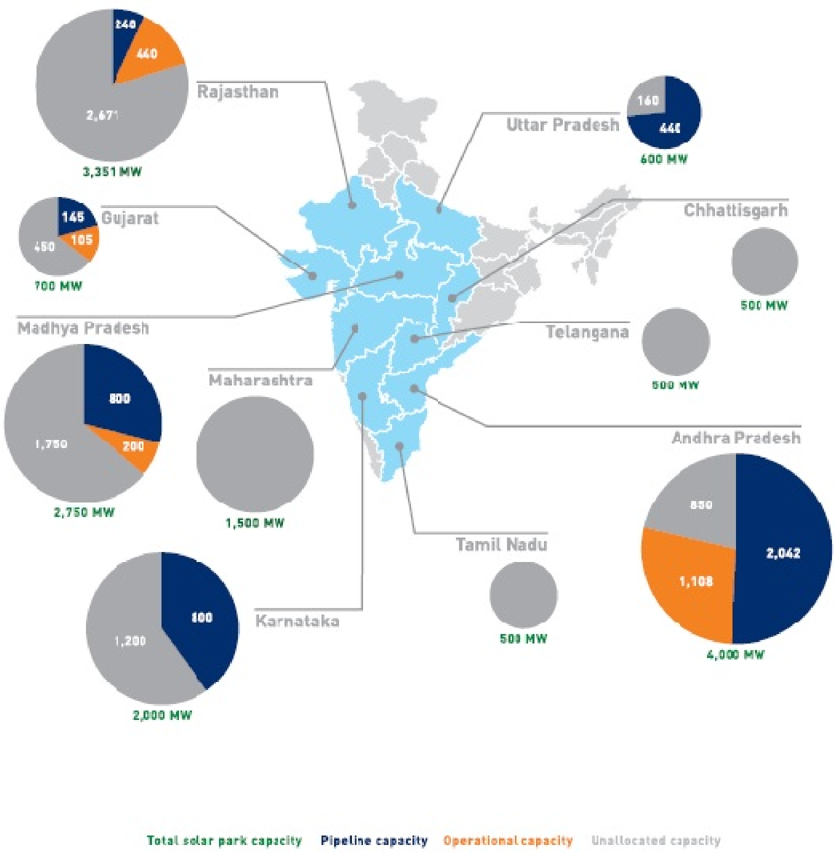

Figure 1.6: States with solar parks in India

- No transmission charges are levied on the interstate transmission of solar/wind energy.
- World is betting on the solar potential of India and is ready to invest in this field. Indian government has allowed foreign direct investment up to 100% for renewable energy generation and distribution projects.

5 largest solar plants in India are

1. Kurnool Ultra Mega Solar Park in Andhra Pradesh
2. Kamithi Solar Power Project in Tamil Nadu
3. Bhadla Solar Park in Rajasthan
4. Charanka Solar Park in Gujrat
5. Saker Solar Plant in Maharashtra

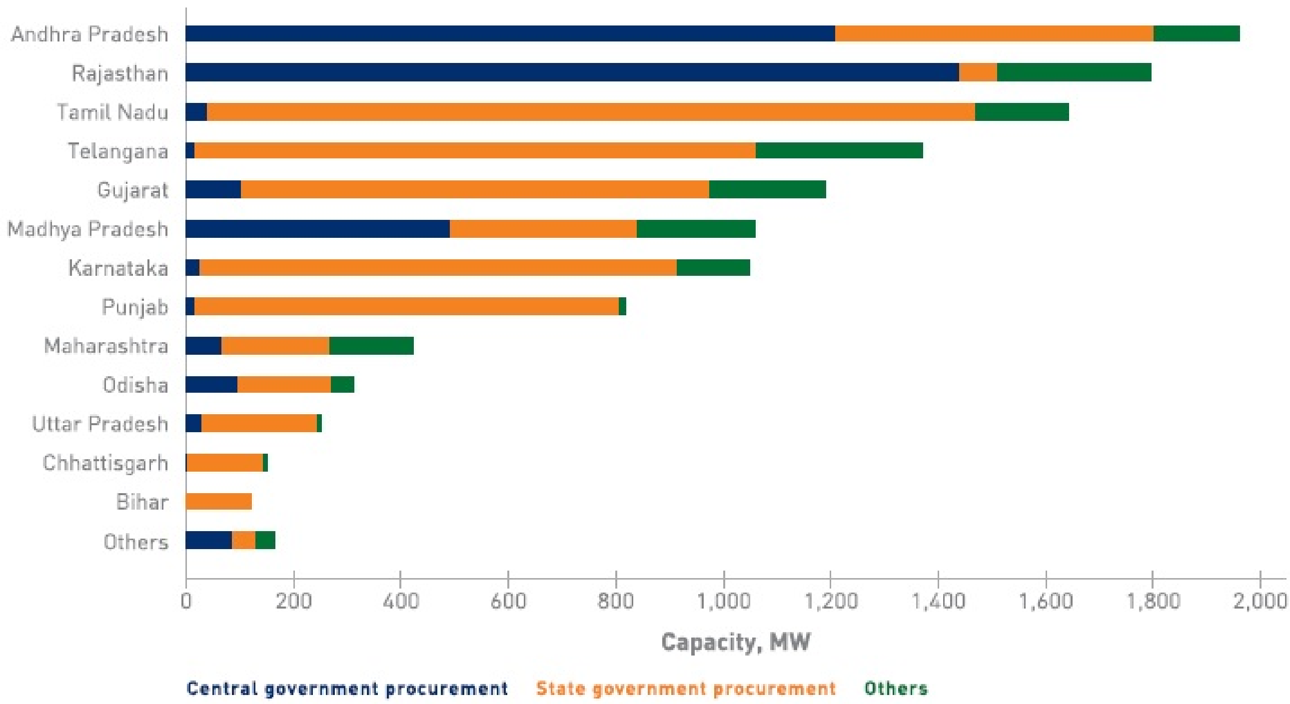

Figure 1.7: Commissioned capacity of various states for solar energy

Figure 1.7 [6] shows the commissioned capacities of various states for solar energy and contribution of central and state government. So to contribute PV technology to power sector grid connected PV systems are set up in various parts of the country. Though such systems are environment friendly but there are many challenges faced by the systems such as voltage fluctuations, harmonics, reactive power control, power quality. These grid-integration issues are to be confronted within the standard such as IEEE 519-1992 and 929-2000 [3, 4]. In order to optimally track the maximum power of PV arrays, maximum power point tracking (MPPT) technique is used in the system. Various control schemes have been developed for the control of voltage source inverter (VSI) which helps in transfer of generated power to the load side by converting it from DC to AC. Compensation of reactive power in grid connected PV system has become an essential requirement of the system in the present scenario. There are various methods to compensate the reactive power like synchronous generator, capacitor bank, PV inverter etc. The research on various control strategies of PV inverter has taken place in last few years so that control of active power is supplemented with the management of reactive power. Due to the necessity of reactive power compensation in the system, the dissertation work presents one such control scheme applied to the VSI in grid integrated PV System.

1.2 Grid Connected Photovoltaic System

Due to concern regarding environmental issues linked with the use of fossil fuels, energy security and rising fuel cost, the interest of utilization of renewable energy sources has been found. Despite this high interest, not a significant number of grid-connected PV systems are visible at present as compared to the traditional energy sources like wind, oil, coal, hydro, gas, nuclear and wind. PV systems have been connected to grid mainly at sub-transmission level. Representation of PV system connected to grid is illustrated in Figure 1.8.

PV array

PV cells being a fundamental unit are connected in such a way (i.e. in series or parallel) to form a higher rating device called PV panel which further forms PV arrays. Polycrystalline silicon cells are mostly used to make PV arrays. The relationship between voltage and current, between voltage and power of the cell are the parameters which are explained by the electrical characteristics of a PV cell.

DC-DC Boost Converter

The output of PV array depends on irradiation as well as on temperature. As both of these pa-

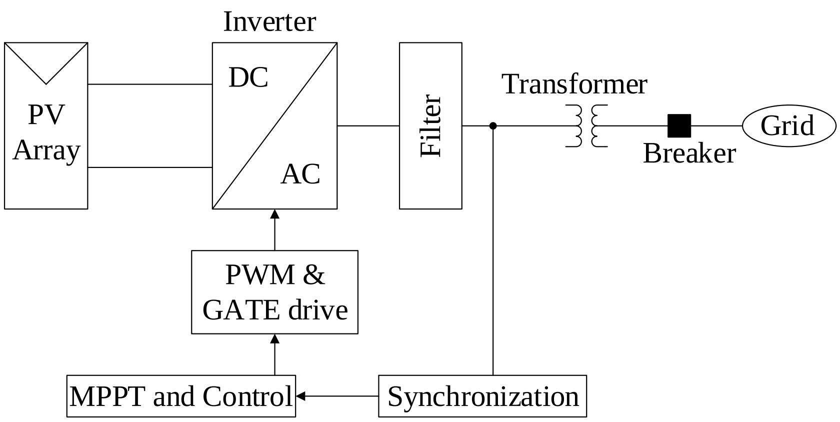

Figure 1.8: Representation of PV system connected to grid

rameters change, the value of voltage produced by PV cell change. The voltage required by the system is constant. So to control and boost the value of voltage produced by PV cell, DC-DC boost converter is used which converts the unregulated DC input (output of array) to controlled DC output of required voltage. To control the switching of converter, MPPT technique is used which changes the duty cycle and send control signal to the switch used in boost converter.

Inverter

DC power produced by the PV array is converted to AC before supplying to grid. This work is done with a device called as inverter. Multilevel inverters are generally employed in the system because as the level increases, the steps in output waveform also increase which generate an output staircase wave which is very close to the desired waveform. Also the harmonics are reduced by the proper control scheme which is used for the inverter. Inverter has semiconductor devices in each phase leg and the switching of these devices is performed with pulse width modulation (PWM) techniques which are classified as carrier based and space vector based PWM methods. Inverter is usually interfaced with the grid through power transformer.

Other components

- **Filter**: The output quantity of an inverter (voltage in case of VSI and current in current source inverter) is pulsed and contains switching harmonics along with a 50 *Hz* fundamental. The location of the filter is decided in such a way that the output voltage of inverter becomes purely sinusoidal before it is fed to the grid [22].

- **Storage Devices**: The installation of storage devices in the PV system plays a significant role to enhance the performance of PV system, various storage devices as batteries, water pumping, supercapacitors, flywheels etc. which vary in their operation as per their application.

1.3 Importance of Reactive Power Compensation in Grid Connected Photovoltaic System

Several challenges and issues are faced by the distribution utilities because of the high penetration of distributed generation into the electrical system. The variation in irradiation can cause voltage swells and sags which can affect the power quality. To control the reactive power in a system, many techniques have been developed with which power quality of the system can also be improved. There are various methods to control the reactive power which includes synchronous generator, capacitor banks but have certain limitations.
In order to maintain the voltage regulators, photovoltaic inverters can provide the required reactive power which is needed in the system due to the nonlinear loads which are connected to the system. This type of compensation belongs to the category of end-user reactive compensation technology. It has several benefits:

- Efficiency: As this type of reactive compensation is near to the user end so average value of current which flows through the system is less and therefore thermal loses are reduced by this.

- Scalability: Large number of capacitor banks expand the distribution system and add many constraints to it. Moreover, the capacitor banks require coordination which is not the problem with the local compensation.

- Reliability: If the system relies on large capacitors there are chances of equipment failure which can be avoided with the compensation provided by the PV inverter.

1.4 Literature review

The literature review for understanding the basics of PV system, various challenges that are face by its integration with grid and different control schemes is given in Table 1.1.

Table 1.1: Literature Review

$Sr.No.$	Authors	Contribution
Photovoltaic System		
1	Villalva et al. [40]	Representation of PV cell was given as a constant current source having a diode which is connected in parallel, equivalent diagram of PV array having a resistance connected in series and in parallel. Modeling of the PV array was explained with the help of equations using MATLAB/Simulink.
2	Islam et al. [18]	The effect of change of irradiation was explained on PV and IV curves obtained from PV array. As irradiation decreases, it reduces open circuit voltage (V_{OC}) and decreases the value of short circuit current (I_{SC}).
3	Chander et al. [15]	The effect of variation of temperature was explained on I-V and P-V curves obtained from PV array. With the increase in temperature the open circuit voltage (V_{OC}) decreases and short circuit current (I_{SC}) increases but very significantly.
Grid Connected PV System & its challenges		
4	Carrasco et al. [13]	Role of development in power electronics in wind and solar systems was explained focusing different inverter topologies using Simulink. Modeling of different components of Grid Connected PV system was done including all stages MPPT technique, inverter control scheme & filter design.
5	Ropp and Gonzalez [30]	Though integration of renewable energy sources with grid had improved with the technical development and had become important in power sector but the issues related to the connection of PV with grid were highlighted and appropriate measures for the same were discussed.

Continued on next page

Table 1.1 – *Literature Review Continued*

6	Katiraei and Aguero [20]	The discussion related to various issues like voltage fluctuations, reverse power flow, reactive power requirement, power quality issues, etc. are faced in grid connected PV system for which proper solution is required was carried out.
7	Turitsyn et al. [38]	Importance of reactive power control was an important issue which was discussed and various methods to control reactive power like synchronous generator, capacitor banks, PV inverter etc were explained.
8	Rizy et al. [29]	Detailed analysis of a PV system integrated with grid was done with and without VAr control which emphasised the importance of the VAr compensation.
MPPT		
9	Kumar and Singh [25]	Importance of MPPT technique was discussed with the application of Perturb and Observe (P&O) to PV system.
10	Kish et al. [23]	The incremental conductance(INC) MPPT technique was another common method for MPPT used in small and medium power applications was described with its application in PV system.
11	Subudhi and Pradhan [35]	Different MPPT techniques were compared and their application in different systems was discussed.
Grid Connected VSI & Control Scheme		
12	Kumar and Singh [24]	INC is used to obtain maximum power in addition to the precision quadrature control which derives the fundamental current from the given load at any instant and compares with reference current under different operating conditions.
13	Malesani and Tenti [26]	Discussion related to hysteresis band control method for the current controlled 3-phase VSI was carried out. It does not require any load parameter but had the drawback that modulation frequency diverges in a specified band and cause many ripples.

Continued on next page

Table 1.1 – *Literature Review Continued*

14	Malesani et al. [27]	Problem of [26] was solved as modulation frequency was nearly constant with the help of some system constraints which was further improved in [10] by adjusting analog prediction of the hysteresis band to phase locked loop (PLL).
15	Kawabata et al. [21]	[27, 10] can't be used for unbalanced system, so an algorithm for dead beat current loop and voltage loop was derived for dead beat controller whose improved algorithm was given in [11].
16	Atia and Salem [7]	Application of deadbeat controller in PV system was explained.
17	Shah and Sensarma [32]	It introduced proportional integral (PI) controller in stationary reference with inner voltage control. But its transit response was poor as well as settling time was high.
18	Suhas and Rajguru [36]	Used two VSI control strategies: PI control and proportional resonant control (PR). The former was used in d-q reference frame which the latter was used to minimize the steady state dc error.
19	Vasquez et al. [39]	Proposed two level control method, primary and secondary control; primary one includes the droop method for active & reactive power control whereas the secondary one controls the frequency as well as magnitude deviances.
20	Hsu and Behnke [17]	Introduced two PI controllers for +ve & -ve sequence, experimental & simulation results prove that -ve sequence compensates the effect of loading in system.
21	Cecati et al. [14]	Proposed a H-bridge multilevel converter with fuzzy logic controller which did not require PWM switching angle generator and PI controller. Results for PV & PQ control were explained.
Reactive Power Control		

Continued on next page

Table 1.1 – *Literature Review Continued*

22	Demirok et al. [16]	Importance of reactive power was explained and different methods to control reactive power in grid integrated PV system were explained.
23	Schonardie et al. [31]	Presented Simulink modeling of PWM inverter and application of a control scheme using dq0 transformation control strategy was used for voltage regulation.
24	Tsengenes and Adamidis [37]	The use of p-q theory was done and control strategy which supplied active power to the grid and compensated reactive power of the load.
25	Wandhare and Agarwal [41]	Control strategy with help of proper switching was used for two converters in which primary converter supplied active & reactive power all the time & auxiliary worked only when power factor dipped below a certain value. It claimed to improve reactive power by 300%.
26	Cagnano et al. [12]	Optimization procedure involving the sensitivity theory along with Lyapunov function was being used which provided control laws that acted as reference to controller and controlled the reactive power.
27	Singh and Solanki [34]	Comparison of various algorithms instantaneous reactive power, load balancing theory, synchronous reference frame (SRF) theory was done which explained the application of each algorithm in different conditions.
28	Kandpal et al. [19]	Smart PV distribution static compensator (DSTATCOM) having an adaptive reweighted zero attracting control algorithm along with P&O MPPT technique was applied for supplying power to the grid and the load.

Continued on next page

Table 1.1 – *Literature Review Continued*

29	Beniwal et al. [9]	Another control using modified least mean fourth (MLMF) algorithm for voltage source converter (VSC) in three-phase, four wire system with DSTATCOM capabilities compensated the reactive power, corrected the power factor with high efficacy at high voltages.
30	Singh and Dwivedi [33]	It discussed the two stage PV system having resonant based control algorithm which feeded power to the network, reduced harmonics, balanced the load etc. INC MPPT method was used for the converter to track the maximum power.

Figure1.9 describes the organization of literature review according to different areas which were extensively studied.

1.5 Objective

The control of certain parameters is vital to keep them within the limits described by some standards. To efficiently transfer the power produced by PV array to the grid, reactive power management is essential. Control of the reactive power in PV system connected to the grid is the objective of this dissertation work. This is done by modeling a PV system connected to grid in MATLAB/Simulink.

- Comprehensive study of the literature related to the PV system
- To design a PV solar array
- To design a boost converter and application of P&O to get the maximum power from PV array
- To design a control strategy for three phase voltage source inverter which can compensate the reactive power, maintain power factor of the distribution system

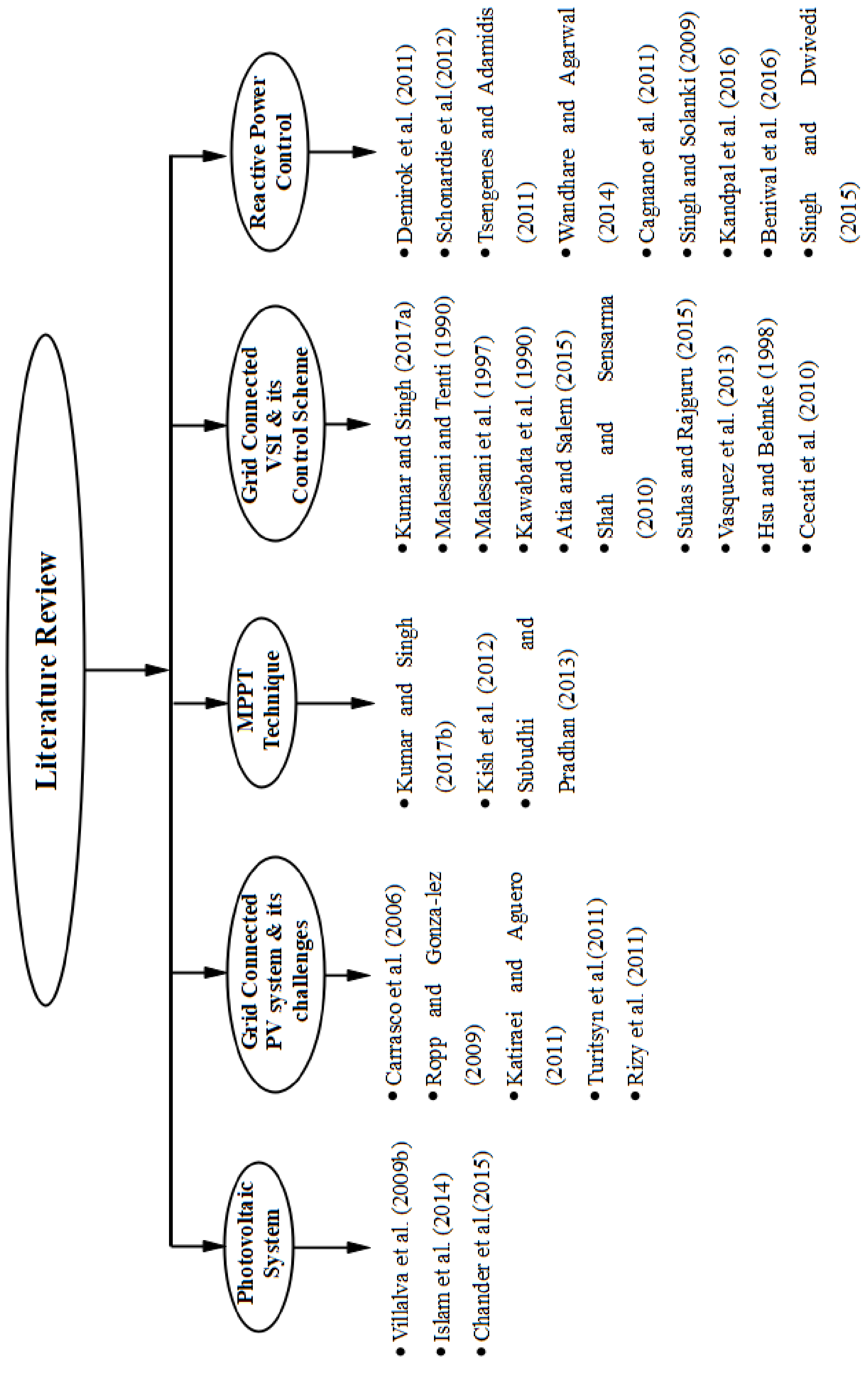

Figure 1.9: Literature Review

1.6 Organization of Dissertation

To fufil above mentioned objectives, the dissertation is organized as follows:

1. Chapter 2 discusses the evolution of PV technology, various materials used, equivalent circuit of PV cell and modeling of PV array.
2. Chapter 3 presents the design of DC to DC boost converter along with of VSI and discusses the (P&O) MPPT technique for boost converter and control scheme for controlling VSC.
3. Chapter 4 Simulink implementation of various components of grid connected PV sytem is carried out.
4. Chapter 5 discusses the reactive power control with the help of the Simulink results and discusses about the power factor improvement and load balancing.
5. Conclusion and future scope are summarized in Chapter 6.

Chapter 2

PV Electrical Systems

2.1 Evolution in PV Technology

Though photovoltaic system used today is around 60 years old but discoveries related to the solar cell started way back 200 years ago because of which PV system that exists today is possible. Development of PV technology in chronological order is explained below.

1839: Discovery of PV effect

PV effect was discovered by a French scientist Edmond Bacquerel in 1839. It explained the creation of electrical voltage when sunlight is absorbed by a material.

1873-1876: Photoconductivity of selenium was discovered

In 1873, Smith an English electrical engineer discovered that Selenium becomes electrically conducting when it absorbs light. In 1876, after 3 years it was found that electricity can be produced from light without any moving parts or heat.

1883: Creation of first solar cell

By coating selenium with a layer of gold first solar cell was created with 1-2% energy conversion rate.

1887: Observation of PV effect

It was observed that free electrons were created when light falls on a solid surface and created power. This was observed by Henrich Hertz which he explained for ultraviolet light. Albert Einstein later explained it for visible light for which he got Nobel Prize.

1953-1956: Production of solar cells for commercial purpose

Scientists at Bell Laboratories discovered that Silicon has greater efficiency than selenium and created first silicon cell with 6% efficiency.

1970s: Cost of solar cells decreased

In 1970 demand for solar power increased due to increase in price of oil. National Renewable Energy Lab (NREL) developed cells made up of very low grade silicon which were low in cost and efficiency.

1982: First solar park was created

In 1982 first solar park was set up at California by Acro Solar that generated 1000 kilowatts per hour.

1994-1999: New solar cells with higher efficiency were formed

In 1994, NREL developed new solar cells made up of gallium, Indium phosphide and gallium arsenide that had conversion efficiency of about 30% followed by the creation of thin film solar cells with 32% efficiency at the end of the century.

2005: DIY solar cell panel became popular

Due to increased use of PV system at residential and commercial sites the use of DIY panels increase as they provide a flexible way to design a solar array as per the requirement.

2015: Solar cells were formed using industrial printer

Solar cells with the thickness of a paper are manufactured in industry using printers which have 20% conversion efficiency. They are flexible and economic as a single strip is able to produce 40 watts per square metre.

2.2 Photovoltaic materials

Silicon continues to be the most widely used material for the manufacturing of PV cells. The maximum research has been done on silicon out of all semiconductor materials because of its unmatched efficiency and reliability.

There are basically 3 technologies used for the manufacture of PV cells and they are listed below and classification of these technologies is shown in Figure 2.1.

1. Wafer based silicon cell
2. Thin film cells
3. New emerging Technologies

Wafer based Silicon Technology has three types of cells and are classified as:

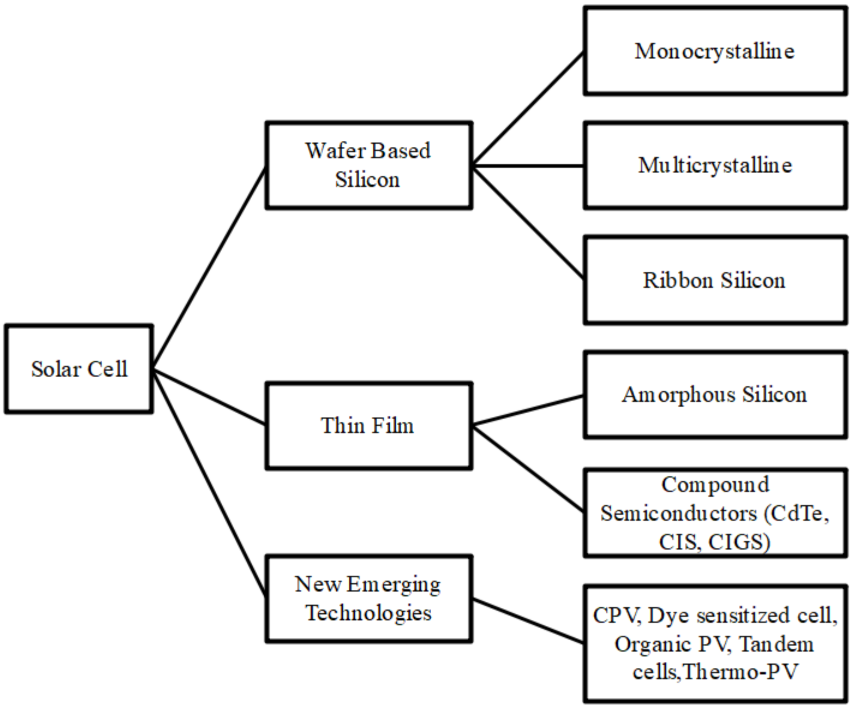

Figure 2.1: Different types of photovoltaic materials

1. Monocrystalline or single crystal silicon cell

This type of cell is made up of a single silicon crystal that is then sliced into wafer. The efficiency of these cells varies between 13% to 15%. It has grain size of more than 10 cm. It is efficient type of cell as it does not have grain boundaries which decrease the thermal as well as electrical conductivity of the material.

2. Polycrystalline or multicrystalline cell

They are made from multiple crystals of silicon and are then sliced and doped. Multicrystalline cells have grain sizes as 1μm -1mm whereas polycrystalline cells have between 1mm-10 cm. In case of nanocrystalline cells grain size is less than 100 nm. They are dominant in the market and will remain till 2020 due to its proven reliability.

3. Ribbon silicon cell

Ribbon growth is used to produce multicrystalline silicon strip. It lashes down the price of cell as less silicon is used in ribbon than in wafers. The wastage of silicon which is high in wafers is cut down in ribbon silicon cell but the efficiency of ribbon i.e. 13% to 14% which is less as compared to that of wafer i.e. 18% to 20%. Some of the semiconductor materials like indium antimonide, gallium arsenide, indium phosphide and aluminium gallium arsenide are used for making the solar cells because they have high efficiency at higher irradiance and they are basically used for concentrating devices. Around 40% efficiency have been investigated but these cells are not commonly used.

Thin film cells

The price of solar cell is high as silicon wafers used in its manufacturing. Inorder to cut down its price thin film technology came into picture. The materials used in this are very strong absorbers of light and the thickness is also less. Hence, the material used is less and cost is reduced. Thin film cells that are commercially available have very less efficiency that is 10% which is very less as compared to the efficiency of the crystalline cells.

1. Amorphous thin film cells

Amorphous silicon cells were the first type of thin film cells that were developed with the efficiency of about 2% to 5%. Micromorph cells commonly named as thin hybrid silicon cells were produced by the combination of monocrystalline silicon cells and thin amorphous cells to get higher efficiency.

2. Semiconductor cells

Some of the semiconductor materials like indium antimonide, gallium arsenide, indium phosphide and aluminium gallium arsenide are used for making the solar cells because they have high efficiency at higher irradiance and they are basically used for concentrating devices. Around 40% efficiency have been investigated but these cells are not commonly used.

New emerging technologies

Dye-sensitized solar cells and organic PV cells form the class of technologies developed recently. Though both of them have not been used commercialized but research has been done and they are called as third generation of solar PV technology. These cells are simple in their manufacturing and low in cost. The laboratory efficiency for dye sensitized solar cells have been achieved around 15%. Organic cells are made up of organic materials and are inexpensive but are not very efficient. The laboratory efficiency of organic cells is 4% to 8%. Such low efficiency is the only reason that these cells have not been commercialized.

2.3 Various topologies of a PV system connected to grid

There are certain ways with which PV inverter is connected with PV array, broadly the classification goes as single stage PV system and two-stage PV system. These different methods of connection are called as topologies.

Single stage PV system

A system in which PV array is connected to inverter is termed as single stage PV system which is illustrated in Figure 2.2. Such a system has a single device as power conditioning unit i.e. inverter to perform all the functions like application of current control scheme, MPPT technique etc. A single step process of transfer of power from PV source to grid is having step up transformer which is incorporated in the system to increase the voltage level of the system. The power factor of such a system is low i.e. around 0.6 to 0.7.

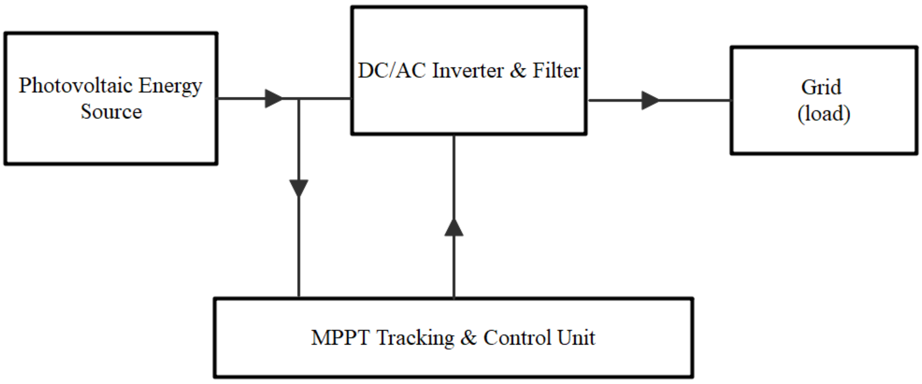

Figure 2.2: Block diagram of a single stage PV system

Two-stage PV system

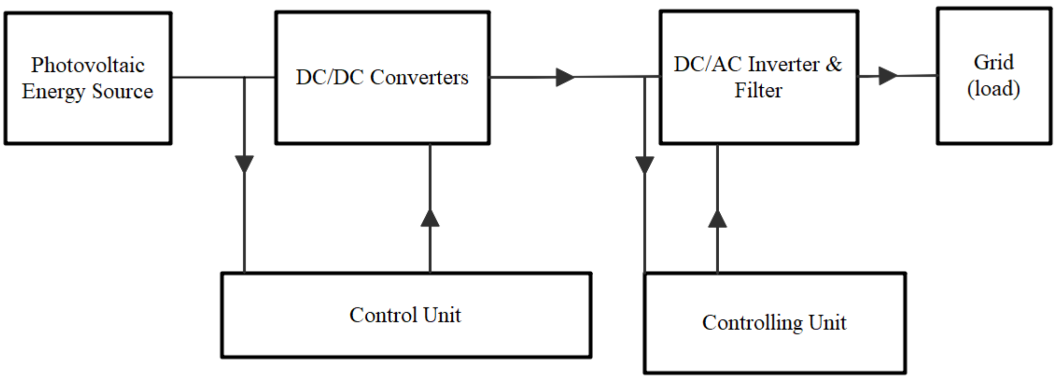

Figure 2.3: Block diagram of two-stage PV system

The use of DC-DC boost converter in such a topology is there to increase the voltage level and to make the system operate at maximum power point which is done with the help of some MPPT technique. Another device that follows boost converter in the system is DC-AC inverter whose control scheme is responsible for controlling the grid current. Such systems have low level of reliability, high cost and are big in size. Figure 2.3 represents two-stage PV system. Different types of classification of PV topologies exist which more specifically depend on the arrangement with which PV modules are connected to inverter which is represented in the Figure 2.4.

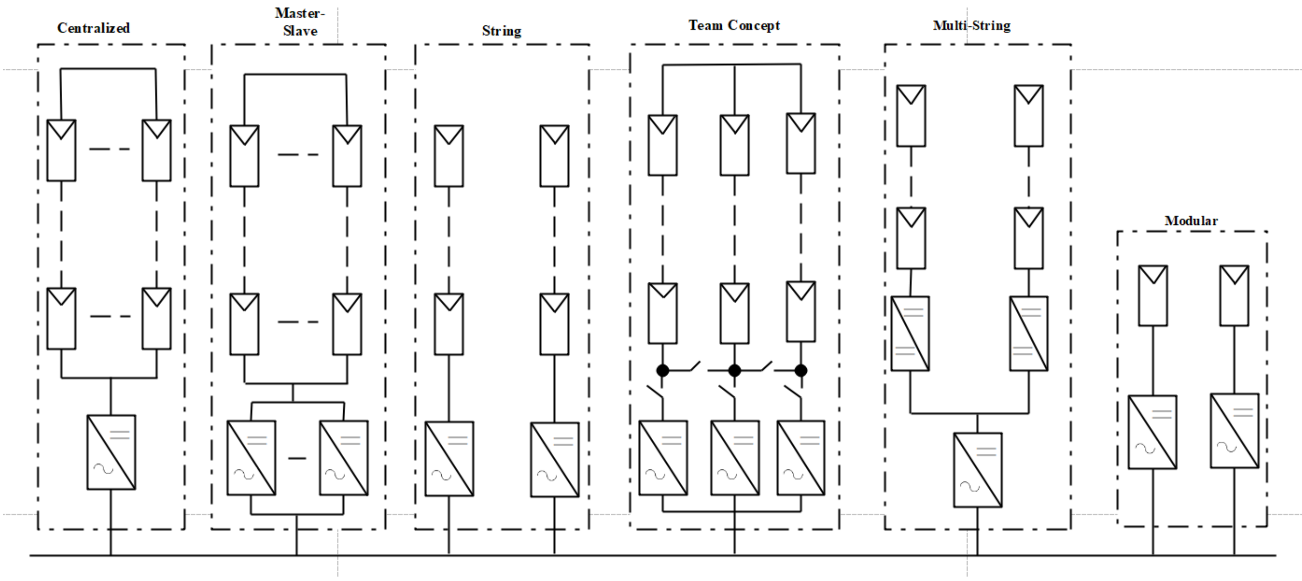

Figure 2.4: Layout of various topologies of PV system

Centralized topology

Some topologies have become established in their study and usage, this topology is the one which is used for the arrangement of different devices in large PV system. There is no requirement of DC-DC boost converter but a single inverter performs both the functions that is to boost up the voltage and to control the current of the system. Due to its low reliability i.e. any problem in the inverter will stop the entire system and significant power loss in inverter for tracking maximum power point this topology is not used for small systems. The only advantage this type of topology has is low cost and ease of maintenance due to less number of components.

Master-Slave topology

As discussed in previous topology, there are certain drawbacks of using a single inverter. This topology is used to improve those shortcomings and make the system more reliable. A set of inverters is used in parallel from which it is decided how many inverters will operate and which one will replace the other if some fault occurs in the one that is selected for the operation. With an inverter ready to replace the one which has become nonoperational makes the system more reliable. To make the system work at higher efficiency and for adding more years to the life of inverter the operational time of the inverter is controlled which is dependent on the level of irradiance. By doing this the life of inverters increase and operating efficiency also boost up.

String topology

In order to make the system more reliable, the connection of every PV array in a string is made with inverter. The system becomes flexible enough that at the time of requirement new strings can be added easily to the system. The increased cost is the only disadvantage of this topology.

Team concept topology

For the PV systems of higher ratings this topology which is a combination of string and master-slave topology is used. When the irradiation is more, PV array gets divided into small strings where a string is connected to an individual inverter and operates nearly at rated power and at lower irradiation a single inverter becomes operational.

Multi-string topology

To get the benefits of string and centralized topologies, this topology is used in which every string is in direct connection with DC-DC boost converter which make the system operate at the highest efficiency of PV array. All the converters used in the system are further connected to inverter which is responsible for the control of the current in the system. The losses in the system also increase due to DC-DC converter.

Modular topology

This is recent a topology and is called as AC modules as individual inverter is connected to each module. Better monitoring of the failure of module, flexibility in designing of array and minimization of losses due to partial shading are some of the advantages of this topology but due to its high cost and its application to low power systems this topology is not very commonly used.

2.4 PV cell and its working

The most recognized method of using the solar energy is by converting it into electrical energy with the help of PV installations. Any such material that has the capability to convert the energy of photons of light to an electrical quantities such as current and voltage is called PV material. When a photon of short length and such a high intensity strikes a PV material, it knocks out an electron from it and in a given electric field this electron causes electric current. The PV cells work without creating any noise and pollution and as sun is the only resource required for the working of PV system, they can work for maximum days of an year. PV cells being one of the most reliable products within the category of semiconductor devices has life of around 30 years.

Working of PV Cell

Two words ‘photo’ + ‘voltaic’ together define the word photovoltaic. Photo is a Greek word used for light and difference of potentials is known as voltaic. As per the quantum physics, the light has dual nature. It acts as a particle as well as a wave. Photons are the particles of light which are massless and move at the speed of light in metals and more generally in matter. Electrons are present as valence and free electrons. Free electrons can move freely while valence electrons are bound to atom with the energy called as binding energy. If the valence electron needs to become free, energy equivalent or greater than binding energy is required. In case of photoelectric effect photon provides such energy to electron by collision. The energy of photon is partially used in the process of making an electron free and rest is converted into kinetic energy of free electron. Photoelectric conversion usually takes place in a semiconductor material which has a p-n junction. The structure of a PV cell is shown in the Figure 2.5.

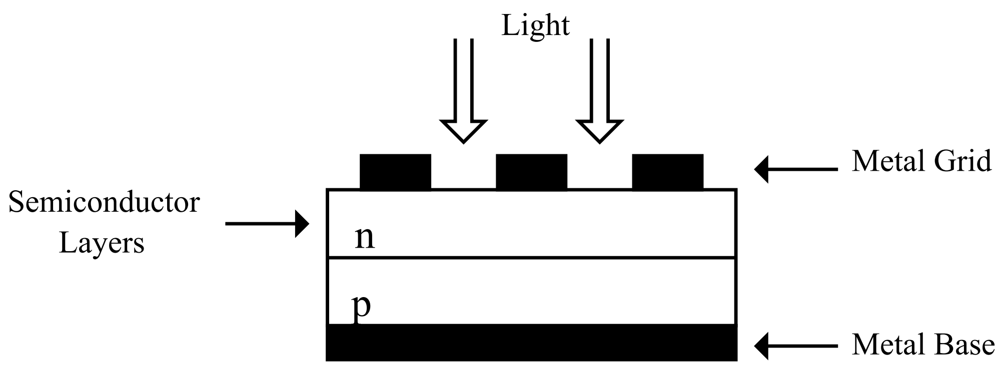

Figure 2.5: Schematic diagram of a PV cell

2.5 Equivalent Circuit for a PV Cell

A constant current source which has a diode connected in antiparallel is represent the equivalent circuit of a PV cell as described in Figure 2.6. The current provided by the current source is directly dependent on the intensity of solar energy that it recieves.

The two quantities which are mainly focused are:

1. Short-circuit current I_{SC}: It is the current which flows on short circuiting the terminals.

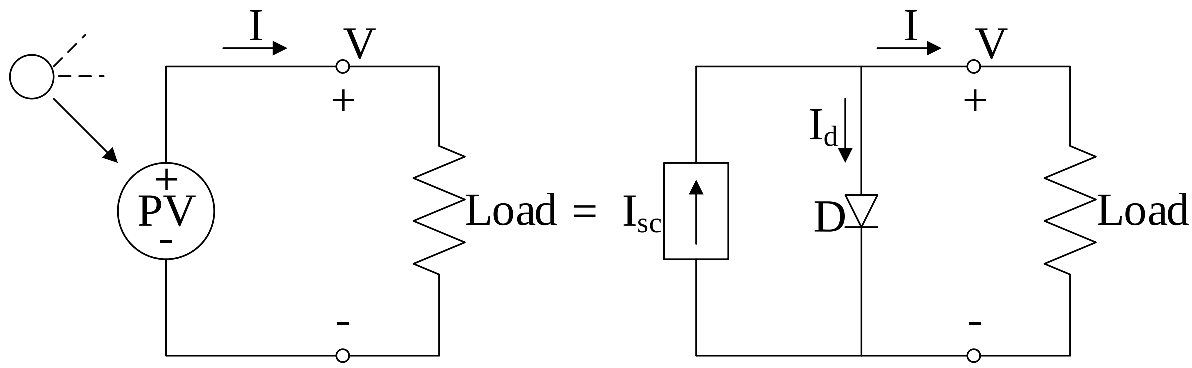

Figure 2.6: Simple equivalent circuit of a PV cell

2. Open-circuit voltage V_{OC}: It is the voltage across the terminals which is obtained when the leads are kept open.

The equation for the equivalent circuit of the PV cell is given in Equation (2.1) is the basic equation for equivalent PV system.

$$I = I_{SC} - I_d \tag{2.1}$$

I_d represents the diode current described by the Shockley diode equation given below in Equation (2.2).

$$I_d = I_0(e^{qV_d/kT} - 1) \tag{2.2}$$

where:

I_d = Diode current (A)

k = Boltzmann's constant = 1.381×10^{-23} (J/K)

I_0 = Reverse saturation current (A)

q = Charge carried by an electron = 1.602×10^{-19} (C)

T = p-n junction temperature (K)

V_d = Voltage across the diode terminals (V)

2.5.1 Modified equivalent Circuit for a PV Cell

The actual circuit of PV cell is somewhat different from the ideal one. A resistance R_p is present in parallel with diode and current source. The value of current provided to load and other components by current source I_{SC} as shown in Figure 2.7 is defined by the Equation (2.3).

$$I = (I_{SC} - I_d) - \frac{V}{R_P} \tag{2.3}$$

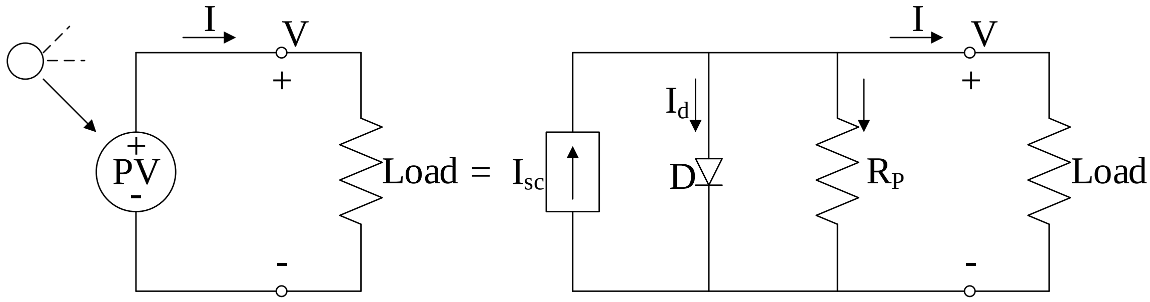

Figure 2.7: Circuit diagram of a PV cell with parallel resistance

The Equation (2.3) depicts the parallel resistance decreases the value load current to V/R_P. The cummulative effect of certain resistances such as contact resistance, leads and the resistance of semiconductor adds to become the net series resistance (R_s) shown in Figure 2.8 [8].

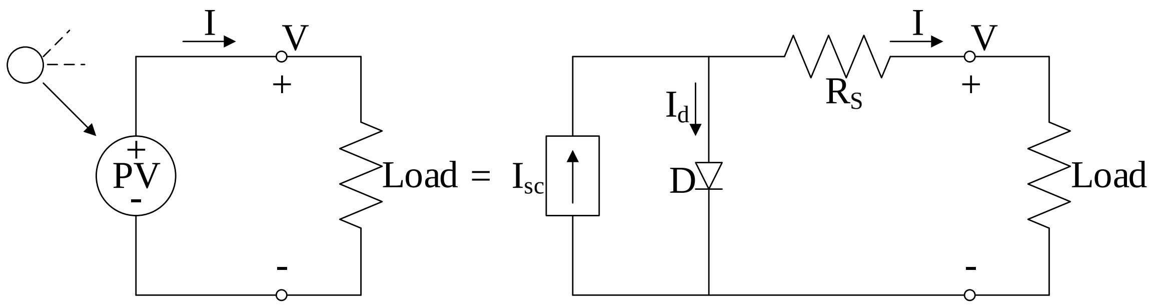

Figure 2.8: Circuit diagram of a PV cell with series resistance

Figure 2.9 presents the modified equivalent diagram of a PV cell. The values of current and voltage change when the effect the series and parallel resistance is considered. The value of current is given by Equation (2.4).

$$I = I_{SC} - I_0 \left[exp \left\{ \frac{q(V + IR_S)}{kT} \right\} - 1 \right] - \left(\frac{V + IR_S}{R_P} \right) \tag{2.4}$$

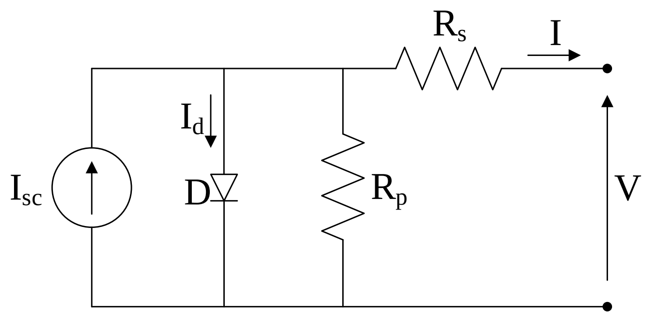

Figure 2.9: Complex equivalent circuit of a PV cell with series and parallel resistance

2.6 Modeling of PV array

The basic unit of PV system is PV cell from which PV modules are made which are further connected to form a PV array of required rating. After absorption of the sunlight PV cell generates the carriers at p-n junction. So capacity of a semiconductor material to absorb the radiation and flux of the sunlight are the factors on which rate of generation of electrons depend upon. There are several factors on which the capacity of absorption of the semiconductor material depend upon such as temperature, semiconductor band gap, electronic mobility, reflectance of the cell, surface recombination rate etc. Figure 2.10 represents the layout diagram of PV array. Strings formed from the connection of PV modules are connected in parallel. This forms a PV array. In the layout diagram a bypass diode is seen which is in parallel with every single module. The function of this diode is to pass the current through it when any module is damaged or is under the shaded condition. Every string contains a diode in series with it. This diode is called as blocking diode which restricts the flow of reverse current and saves the modules from any damage.

I-V and P-V characteristics of a PV cell which are drawn with the help of basic Equations (2.1) and (2.2). But these are the basic equations and are used in the formation of PV array with some modification and is expressed as Equation(2.5).

$$I = I_{SC} - I_0 \left[exp \left\{ \frac{q(V + IR_S)}{V_t a} \right\} - 1 \right] - \left(\frac{V + I.R_S}{R_P} \right) \tag{2.5}$$

in which $V_t = \frac{N_s kT}{q}$ is the thermal voltage of P-V array. I-V characteristics basically depend on R_s and R_p which constitute the internal characteristics of the device along with irradiation and temperature which are the external parameters.

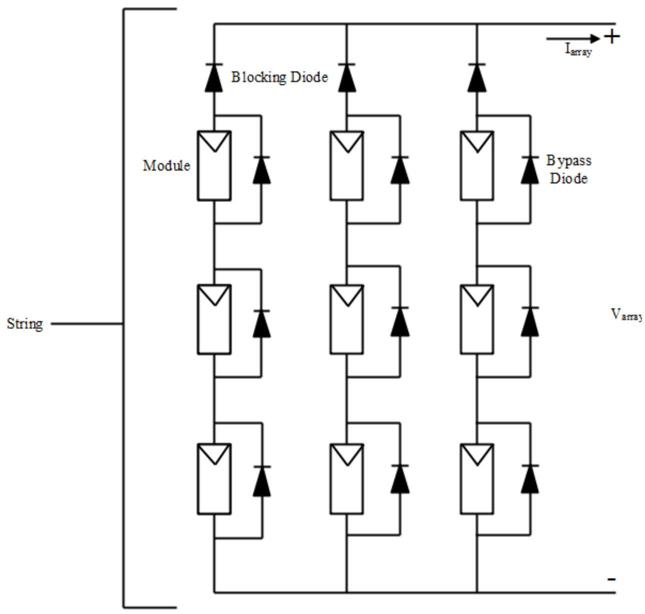

Figure 2.10: Layout of PV array

In Equations (2.1) and (2.5), an assumption that is practically used is considered that $I_{pv} \simeq I_{sc}$ because in a practical PV device series resistance is very less as compared to the parallel resistance. As the current generated in a PV cell depends on irradiation and temperature, so the relation between them is expressed in Equation (2.6).

$$I_{pv} = (I_{pv,n} + k_1 \Delta T)\frac{G}{G_n} \tag{2.6}$$

where:

$\Delta T = T - T_n$

T = Actual temperature

$T - T_n$ = Nominal temperature

$I_{pv,n}$ = Current at STC

G = Irradiation

G_n = Irradiation at STC

The value of saturation current I_o is given by eqn.(2.7)

$$I_o = \frac{I_{SC,n} + K_I \Delta T}{e^{\frac{V_{OC,n}+K_V \Delta T}{\alpha V_t}} - 1} \tag{2.7}$$

The value of R_s and R_p are found with the help of an iterative method [40]. Schematic diagram of PV module for which Equation (2.5) is defined in shown in Figure 2.11. PV array

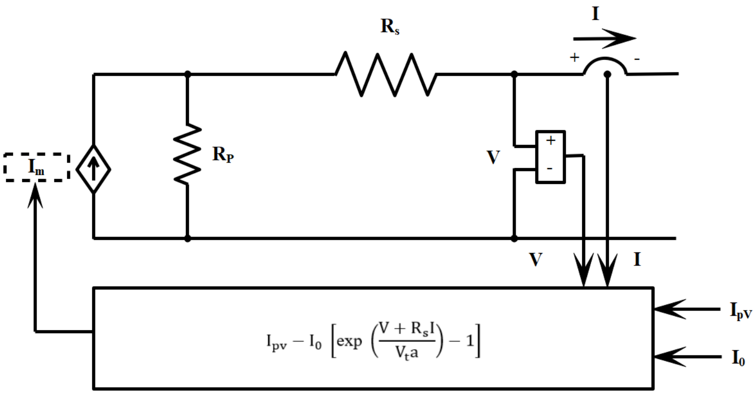

Figure 2.11: Schematic diagram of PV module

is made up of many interconnected PV modules. The modelling of PV array is done in the similar manner as of PV module from the PV cells. The parameters used from the datasheet are same. The number of modules connected in series and in parallel are denoted by N_{ser} and N_{par} respectively.the number of modules change equivalent the series and parallel resistance of the PV array which are

$$R_{s,array} = \frac{R_{s,module} \cdot N_{ser}}{N_{par}}$$
$$R_{p,array} = \frac{R_{p,module} \cdot N_{ser}}{N_{par}}$$

Equivalent series and parallel resistance of PV array changes with the number of modules. Equation (2.8) helps to find the relationship between the current and voltage of PV array.

$$I = I_{pv}N_{par} - I_0 N_{par}\left[exp\left\{\frac{q(V + IR_S(\frac{N_{ser}}{N_{par}})}{V_t \alpha N_{ser}}\right\} - 1\right] - \left(\frac{V + I.R_S(\frac{N_{ser}}{N_{par}})}{R_P(\frac{N_{ser}}{N_{par}})}\right) \tag{2.8}$$

The above given equations will be used to find the value of various parameters during the Simulink implementation of PV array which will be discussed in Chapter 4.

Chapter 3

Design of DC-DC Boost Converter and Control of Three phase VSI

3.1 Modeling of DC-DC Boost Converter

The output voltage of PV array is not sufficient to be supplied to the grid, so there is a need to step up the voltage which is done with the help of DC-DC boost converter. The switching of converter is dependent on the change of duty cycle which is done with the help of MPPT algorithm. The circuit diagram of DC-DC boost converter is illustrated in Figure 3.1. Metal-oxide-semiconductor field-effect transistor (MOSFET) is generally used as a switching device its turn ON and turn OFF time is low which helps to reduces the size of the filter.

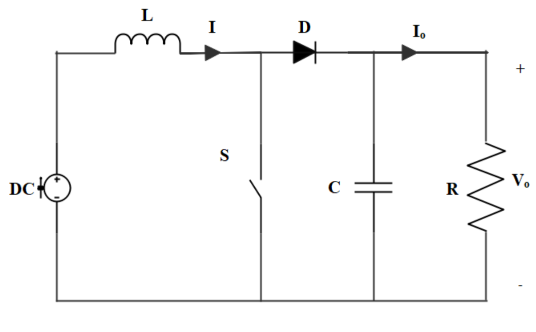

Figure 3.1: Circuit diagram of DC-DC boost converter

The working operation of DC-DC boost converter is explained with the help of equations written below. In Figure 3.1, when S is switched ON, it short circuits the load which means that the output voltage during T_{ON} is zero and in this interval the inductor gets charged. Hence,

$$V_s = V_L \tag{3.1}$$

$$L\frac{\mathrm{d}i}{\mathrm{d}t} = V_s \tag{3.2}$$

$$\frac{\Delta I}{T_{ON}} = \frac{V_s}{L} \tag{3.3}$$

$$\Delta I = \frac{V_s}{L}T_{ON} \tag{3.4}$$

where V_s is the input voltage and ΔI is peak to peak inductor current.

The inductor L which was charged gets discharged through the load when S is switched OFF. The input voltage and the voltage across the inductor contributes to the output voltage.

$$V_o = V_s + V_L \tag{3.5}$$

$$V_L = V_o - V_s \tag{3.6}$$

$$L\frac{\mathrm{d}i}{\mathrm{d}t} = V_o - V_s \tag{3.7}$$

$$L\frac{\Delta I}{T_{OFF}} = V_o - V_s \tag{3.8}$$

$$\Delta I = \frac{V_o - V_s}{L}T_{OFF} \tag{3.9}$$

$$\frac{V_s}{L}T_{ON} = \frac{V_o - V_s}{L}T_{OFF} \tag{3.10}$$

Hence by equating (3.4) & (3.10),

$$V_s(T_{ON} + T_{OFF}) = V_o T_{OFF} \tag{3.11}$$

$$V_o = \frac{TV_s}{T_{OFF}} = \frac{V_s}{\frac{T-T_{ON}}{T}} \tag{3.12}$$

Hence,

$$V_o = \frac{V_s}{1-D} \tag{3.13}$$

where, $0 \leq D \leq 1$

The value of output voltage is always higher than its input voltage as clear from the equation(3.13). The value of boost inductor at k=0.2 is

$$L_b = \frac{V_{MPP}k}{\Delta I_1 f_{sw}} = \frac{615 \times 0.2}{3.84 \times 10000} = 3mH \tag{3.14}$$

where ΔI_1 is ripple current and is considered as 5.5% of output current of array and $I_1 = (\frac{P_{mpp}}{V_{mpp}})$. So the value of boost inductor is taken as 3 mH.

3.2 Maximum Power Point Tracking (MPPT) Technique

The output power of PV array is dependent on atmospheric conditions specially irradiance and temperature which changes the output voltage and current also. For the PV array to deliver output power efficiently, it is made to operate at its maximum power point which is done with the help of MPPT technique which provides reference voltage and current from which reference power can be calculated. The duty cycle generated from the MPPT control is used to control the switch of DC-DC boost converter.

The MPPT algorithms are basically divided into three categories namely model based MPPT algorithm, training based MPPT algorithm and search based MPPT algorithm.

Model based MPPT algorithm

1.Fractional short-circuit current method based MPPT technique In this method PV short circuit current (I_{SC}) is measured at regular intervals and current at MPP (I_{mpp}) is having linear relationship with (I_{SC})

$$I_{mpp} \simeq K_2 I_{SC}$$

K_2 is constant, experimentally found to be 0.78 and 0.92. So, I_{mpp} can be easily calculated.

2.Fractional open circuit voltage method based MPPT technique. In fractional open circuit voltage method PV open circuit voltage (V_{OC}) is measured at regular intervals and voltage at

MPP (V_{mpp}) is having linear relationship with (V_{OC})

$$V_{mpp} \simeq K_1 V_{OC}$$

K_1 is having value as 0.71 and 0.78 which is calculated experimentally.

These methods are simple as well as cheap but lot of power loss occurs in this and efficiency of these methods is low as K_1 and K_2 are found experimentally and may or may not be accurate.

Search based MPPT algorithm

For search based algorithm, the output voltage as well as current of a PV module is sensed. With the help of the measured values of these quantities, PV power is calculated which is further a criteria to decide if the parameters need to be increased or decreased. The switching signals given to the boost converter can be controlled with the help of duty cycle. The search based algorithm requires no knowledge of previous value of the parameters. Hence, it is easy to implement this algorithm. P&O, INC, hill climbing etc. are some of the commonly used search based algorithms. Figure 3.2 represents the schematic diagram of DC-DC boost converter with MPPT.

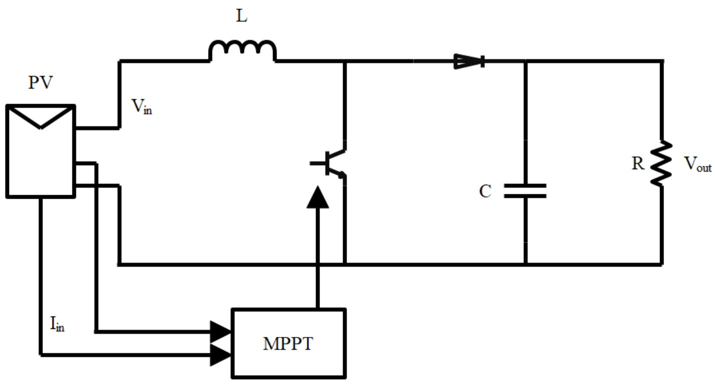

Figure 3.2: Schematic diagram of DC-DC boost converter with MPPT

Perturb and Observe (P&O) MPPT technique

The operating voltage of PV array is perturbed in a particular direction in case of P&O MPPT algorithm and then PV power is calculated from the values of voltage and current which are sensed. After noticing the change in power, the change in operating voltage is decided. The voltage is perturbed in the same direction if the newly calculated power is greater than the previous one and if the power decreases, then voltage is perturbed in the opposite direction. The principle of P&O MPPT algorithm is explained with the help of curve shown in Figure 3.3. The operating point keeps on oscillating around MPP which is the only disadvantage of this method. In this technique the system keeps oscillating around the maximum power point and diverges away from maximum power point when irradiance increases suddenly. To improve this situation many improved versions of this technique are used.

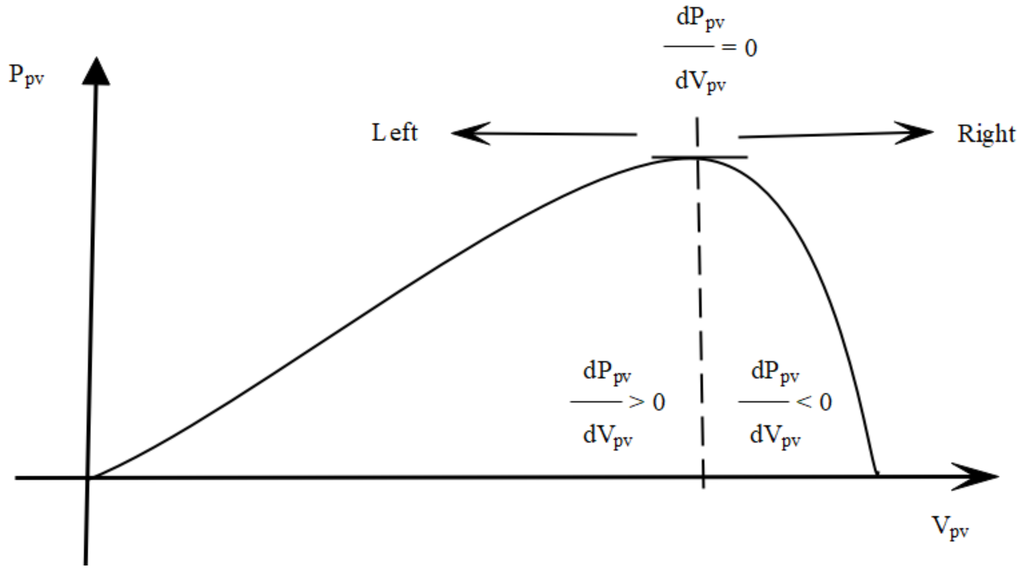

Figure 3.3: Principle of P&O

The algorithm for the P&O MPPT is explained with the help of the flowchart given below in Figure 3.4. PV current and PV voltage are measured from which the PV power is finally calculated. Duty ratio is decided by the sign of the power. Before starting with the algorithm, the duty cycle and PV power are given. At the initial stage, power measured from the PV voltage and current is compared with the given value which was defined initially and then in subsequent iterations the comparison with the previously sensed value is done with the help of which duty cycle can be varied. Duty cycle can vary between 0 & 1.

3.3 Design of VSI

The voltage to be fed to the grid should be AC voltage but the one which is obtained from the PV array and converter is DC voltage. So in order to efficiently transfer the power from source to grid, a device which performs the conversion of voltage from DC to AC is required. This job is performed by inverter. Two level VSI is represented in the Figure 3.5. To control the switching of VSI many PWM schemes are used which can be broadly classified as SPWM, space vector pulse width modulation (SVM), selective harmonic elimination pulse width modulation

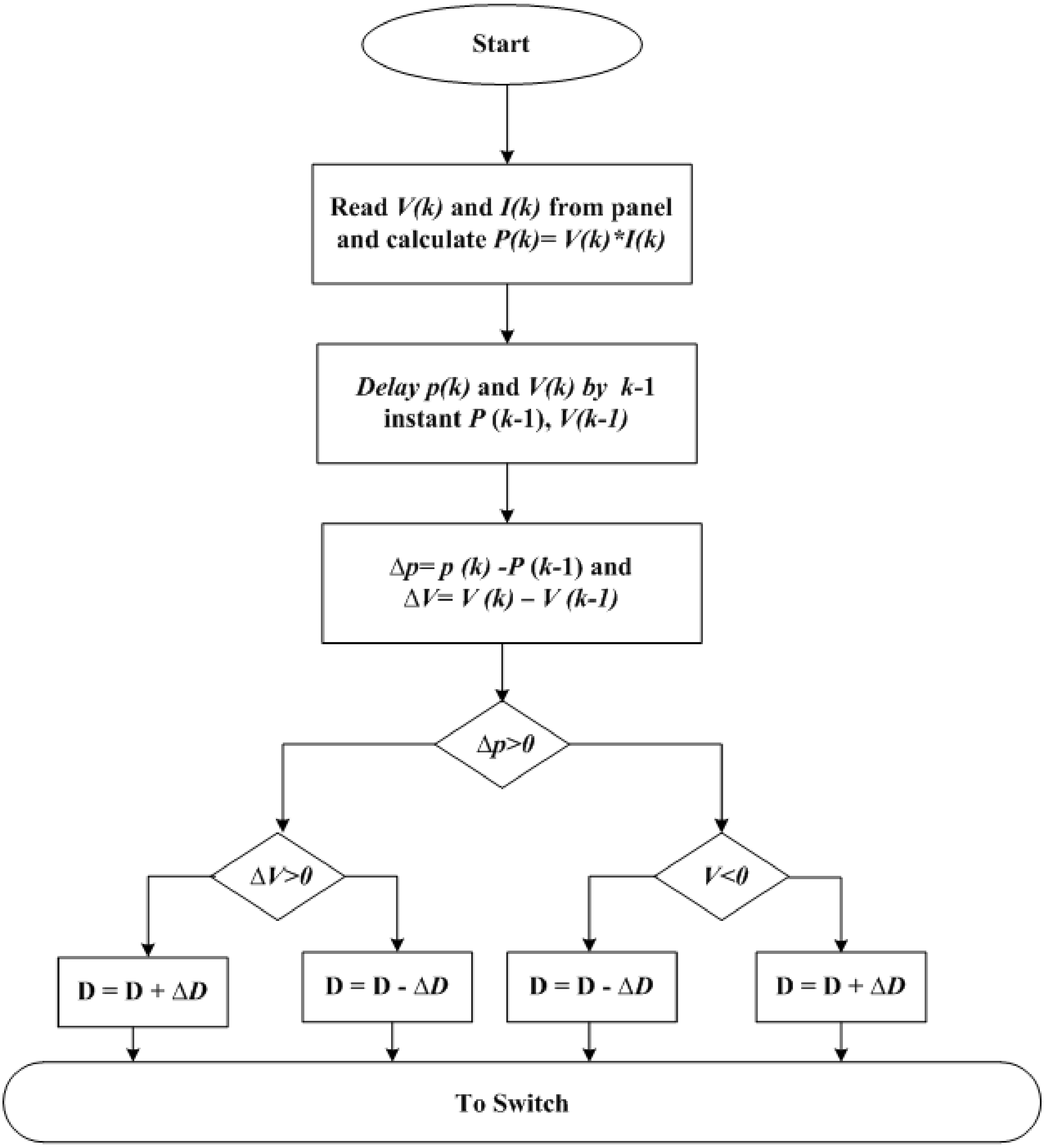

Figure 3.4: Flowchart representing P&O MPPT

(SHEPWM). In SPWM a sinusoidal voltage signal is taken as a modulating signal which is compared with a carrier waveform (high frequency triangular wave) to generate signals for the switches of the inverter [28].

Design of VSC Capacitor Voltage

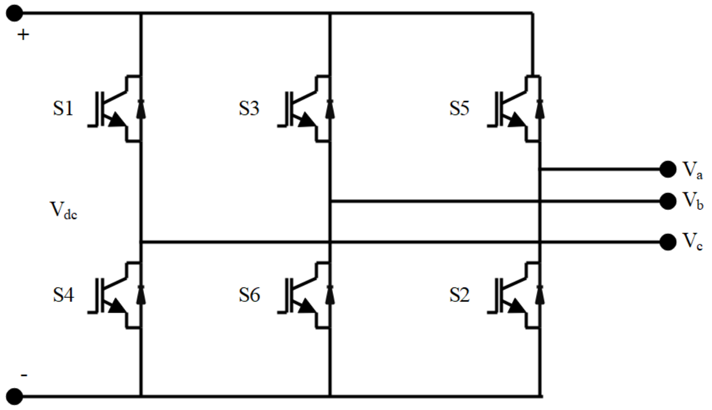

Figure 3.5: Schematic diagram of three-phase VSI

The design of DC link voltageV_{dc} is given in Equation (3.15).

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} = \frac{2\sqrt{2} \times 415}{\sqrt{3} \times 0.956} = 713.27 \simeq 700V \tag{3.15}$$

Where

m = Modulation index

V_{LL}= Line to line voltage of the grid

Design of DC bus capacitor

The value of DC bus capacitor is calculated in Equation(3.16)

$$C_{dc} = \frac{(\frac{P_{dc}}{V_{dc}})}{2 * \omega * V_{crp}} = \frac{\frac{50000}{700}}{2 * 314 * 0.03 * 700} = 5416.1\mu F \tag{3.16}$$

where,

I_d = DC bus current of VSC

ω = Angular frequency $(2\pi f)$

V_{dcrp} = %age ripple voltage which is generally taken as 3% of V_{dc}

So, the selected value of DC bus capacitor is 5416.1μF

Design of Coupling Inductor

Ripple current ΔI_1, switching frequency f_s, loading factor, V_{dc} is considered for finding the value of coupling inductor (L_f)

$$L_f = \frac{\sqrt{3}mV_{dc}}{12hf_s\Delta I_1} = \frac{\sqrt{3}\times 0.95\times 700}{12\times 1.2\times 10^4\times(0.06\times\Delta I_1)} \tag{3.17}$$

$$I_1 = \frac{P_{mp}}{\sqrt{3}\times 415} = 59.82A \tag{3.18}$$

where I_1 is the grid current and ΔI_1 is 6% of the grid current so $\Delta I_1 = 0.06 \times 59.82A$ and substituting this value in Equation(3.17),we get $L_f = 8mH$

3.4 Control Scheme of VSI

Synchronous Reference Frame(SRF) Theory based control is used. It is d-q control theory which is based on the conversion of current from abc frame to synchronously rotating d-q frame of reference. It is one of the best methods to generate reference signals during any disturbance. Its application is simple because it involves only algebraic calculations.The block diagram of SRF method is shown in Figure 3.6.

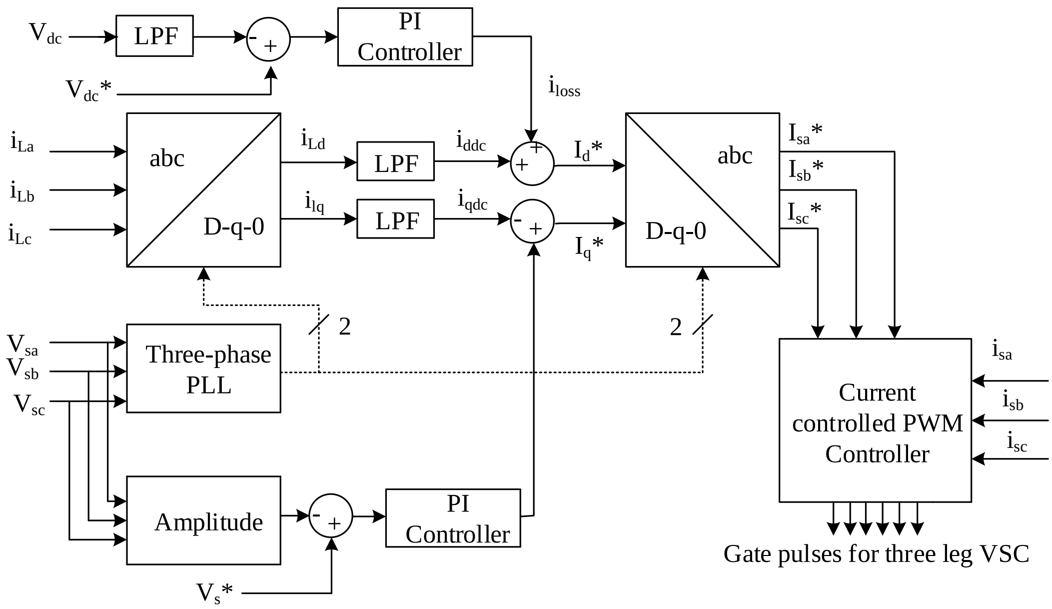

Figure 3.6: Schematic diagram of SRF Theory

There are two voltage control loops used in this control. One control loop is used to control the DC voltage and the other one is for the control of AC voltage. The linear control scheme is implemented as PI controller. The current from the load side is sensed and transformed to d-q frame using abc to d-q transformation. In first control loop grid voltage is sensed followed by the generation of the current component that corresponding the active power demand of the load from grid. Another control loop is for the control of DC voltage, the sensed value of DC voltage is compared with the reference value that is set according to the requirement of the constant voltage that is to be maintained at DC link. Low pass filter is a component that is used to eliminate the higher order harmonics. The current signals generated from the two control loops are compared with current sensed from load side and reference current signals for SPWM are generated. These reference current signals are compared with the sinusoidal current signals sensed from the grid and pulses are generated for controlling the switching of VSI. PLL block is used for vector orientation i.e. sine and cosine signals are generated with the help of voltage signals V_a, V_b and V_c. PI controller is used for the voltage regulation of DC link capacitor i.e. to eliminate the steady state error associated with DC components. In this three phase quantities are converted into two phase quantities i.e. I_{La}, I_{Lb} and I_{Lc} to $I_{L\alpha}$ and $I_{L\beta}$ with help of the following equations called **Clarke's Transformation** given in Equation(3.19).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.19}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{3.20}$$

To convert the current from two phase stationary $\alpha - \beta$ frame of reference to synchronously rotating d-q frame, **Park's Transformation** is used given in Equation(3.21).

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{3.21}$$

In this way three phase unit vector signals are converted to d-q frame to get real components and reactive components Figure 3.7 describes the phasor relationship between all three frames of reference. For reactive power compensation and eliminating the harmonics d-axis current components are used. So the output signals of d-q transformation depend on the value of load current and performance of the PLL. PI controller will control the loss component drawn by the grid from the source. Hence the current generated as a reference current is a sum of loss component and load component. To obtain the desired reference current, d-q components

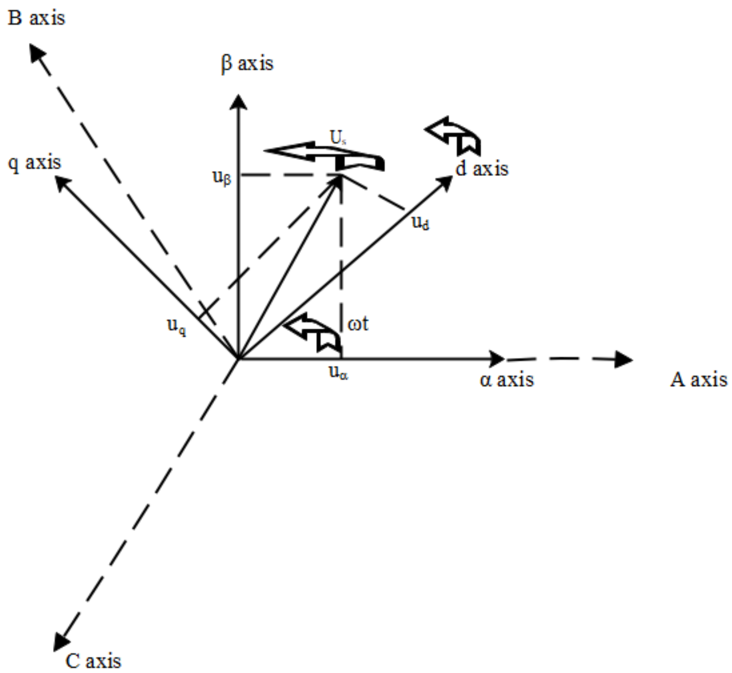

Figure 3.7: Phasor diagram representing the relation between all three frames of reference

obtained from the Park's transformation are passed through the low pass filter from which the DC components are extracted which when added to loss component obtained from the PI Controller generates the reference currents I_d^*, I_q^* in d-q frame which are converted to I_α^*, I_β^* by using Reverse Park's Transformation given in Equation (3.22).

$$\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} \tag{3.22}$$

$$\begin{bmatrix} I_{sa}^* \\ I_{sb}^* \\ I_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_0^* \\ I_\alpha^* \\ I_\beta^* \end{bmatrix} \tag{3.23}$$

Reverse Clarke's Transformation given in equation (3.23) is used to get the reference current in abc frame which is then compared with the sensed grid side current which generates the switching pulses using PWM controller which provides switching signals to VSI.

Chapter 4

Simulink implementation

4.1 Simulink implementation of a Real/Reactive power controller

The grid-imposed frequency voltage source converter (VSC) system is designed to work as a real/reactive power controller. Figure 4.1 reprsents the schematic daigram of current controlled real/reactive power controller.

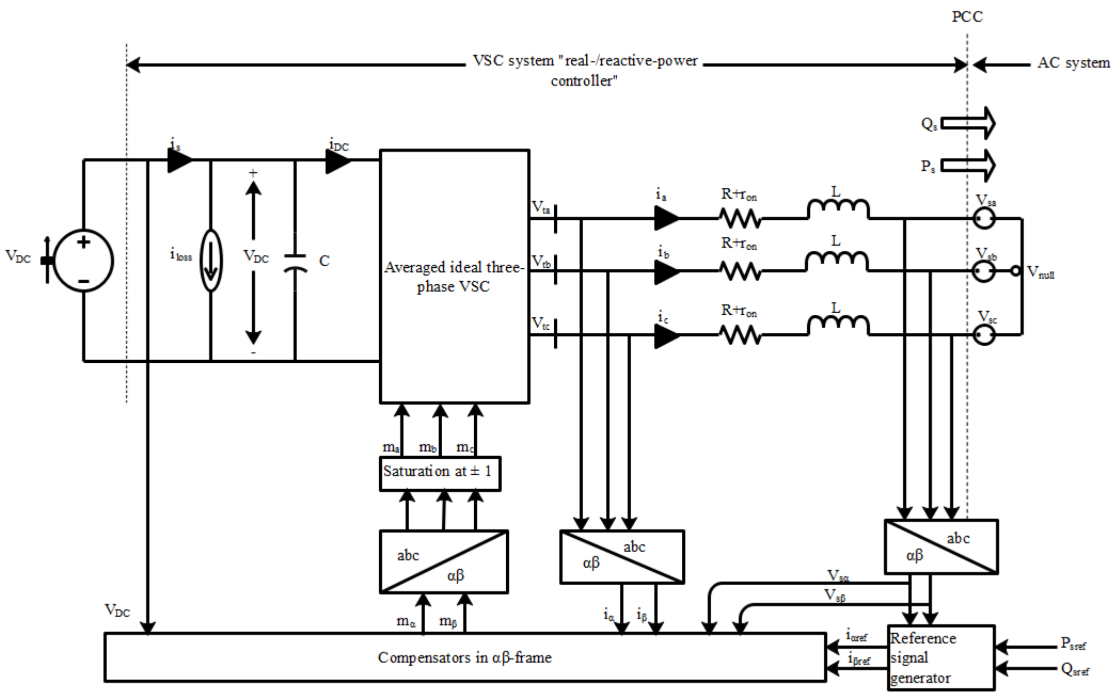

Figure 4.1: Schematic diagram of current controlled real/reactive power controller

The input side of VSC is a constant DC voltage source. The main aim of this work which was done at the initial stage of the dissertation work is to control the value of instantaneous real power and reactive power which is delivered by VSC at the point of common coupling (PCC) [42]. Current control mode is used in this implementation. The control scheme used in this controller works in $\alpha - \beta$ frame of reference. The value of active and reactive powerP_s and Q_s is controlled by α and β components of line current as described in Equation (4.1) and (4.2). The reference signals of current are calculated from the given reference signals of active power and reactive power as described in Equation (4.3) and (4.4)

$$P_s(t) = \frac{3}{2}[V_{s\alpha}(t)i_\alpha(t) + V_{s\alpha}(t)i_\beta(t)] \tag{4.1}$$

$$Q_s(t) = \frac{3}{2}[-V_{s\alpha}(t)i_\beta(t) + V_{s\beta}(t)i_\alpha(t)] \tag{4.2}$$

$$i_{\alpha ref}(t) = \frac{2}{3}\frac{V_{s\alpha}}{V_{s\alpha}^2 + V_{s\beta}^2}P_{sref}(t) + \frac{2}{3}\frac{V_{s\beta}}{V_{s\alpha}^2 + V_{s\beta}^2}Q_{sref}(t) \tag{4.3}$$

$$i_{\beta ref}(t) = \frac{2}{3}\frac{V_{s\beta}}{V_{s\alpha}^2 + V_{s\beta}^2}P_{sref}(t) - \frac{2}{3}\frac{V_{s\alpha}}{V_{s\alpha}^2 + V_{s\beta}^2}Q_{sref}(t) \tag{4.4}$$

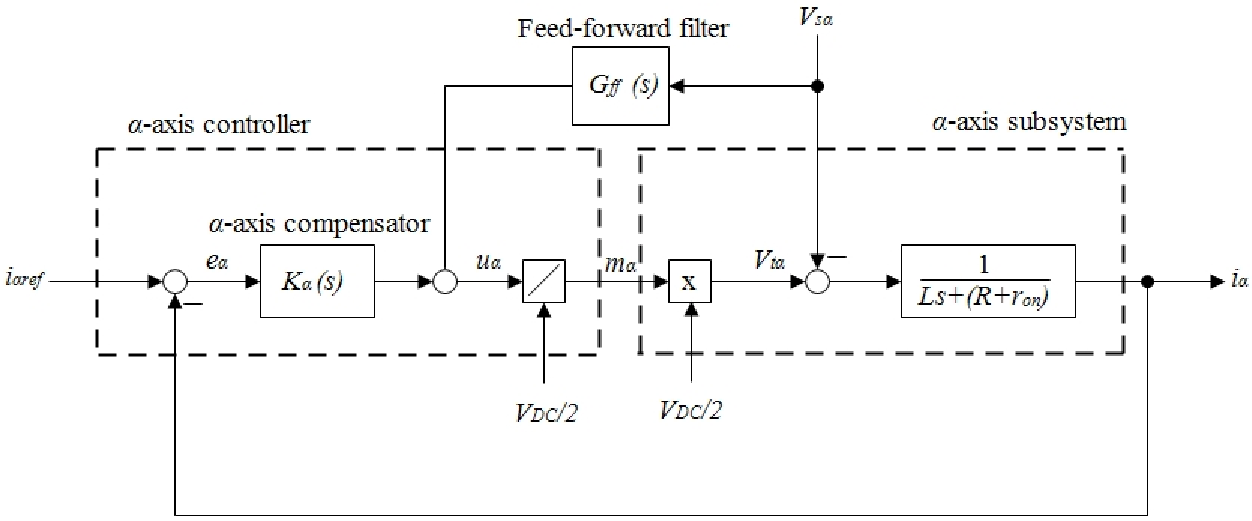

Figure 4.2: Block diagram of current-control loop of VSC for α-axis

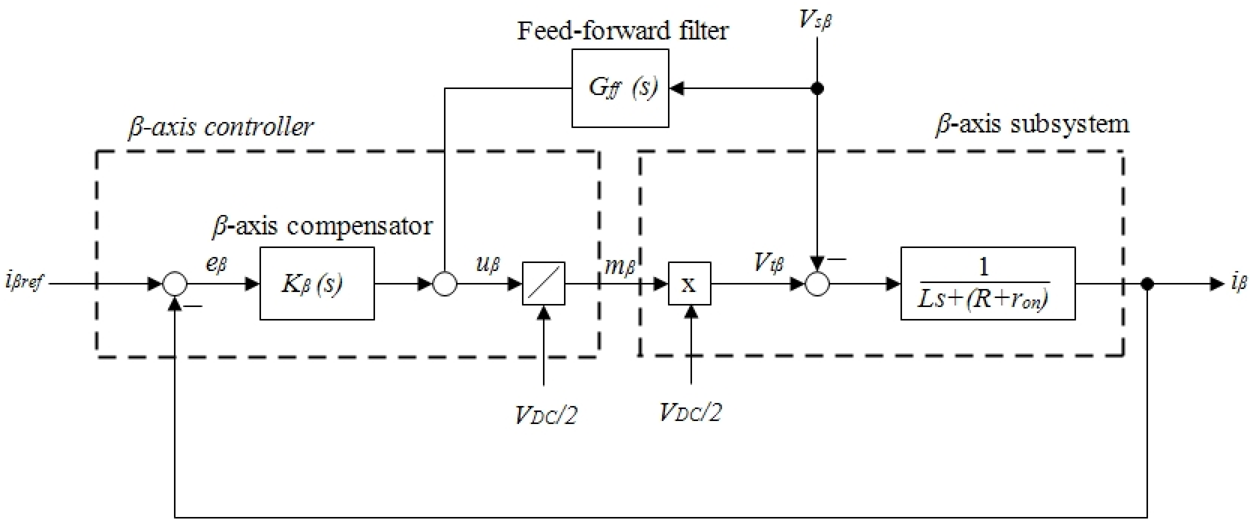

Figure 4.3: Block diagram of current-control loop of VSC for β-axis

To get the control signals in $\alpha - \beta$ frame, firstly the feedback signals are changed to $\alpha - \beta$ frame of reference using Equation (3.21)and are processed by compensators. The control of α-axis and β-axis is done separately as shown in Figure 4.2 and 4.3 which illustrates the current control scheme for α-axis and β-axis.
Before feeding the control signals to VSC, they are transformed back to abc frame of reference using Equation (3.23). The control signals generated are sinusoidal and compared with high frequency triangular wave i.e. SPWM is used to generate control signals for IGBTs used in VSC.

4.2 Simulink implementation of grid connected PV system

4.2.1 Simulink implementation of PV array

PV array is modeled using Simulink. The MATLAB/Simulink model of PV array is realized with the help of modeling technique explained in [40]. The first and foremost step is to obtain the I-V characteristics of PV array. The MATLAB/Simulink modeling of the KC200GT PV array designed for temperature 25^{o}C and 1000 W/m^2 irradiance is illustrated in Figure 4.4. Some of the parameters which are always mentioned in the datasheet and are required in the modeling of PV array are
Open circuit voltage (V_{OC})
Short circuit current (I_{SC})

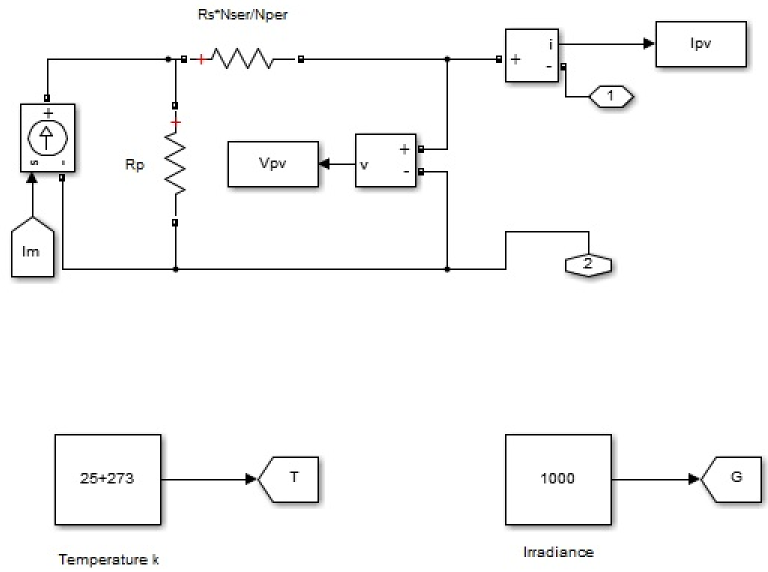

Figure 4.4: Simulink modeling of PV Array

Open circuit voltage/ temperature coefficient (K_V)

Short circuit current/ temperature coefficient (K_I)

Voltage at MPP (V_{mp})

Maximum peak output power (P_{max})

Current at MPP (I_{mp})

The calculation of I_m, I_{pv} and I_o is based on [40] and the equations required for the calculation of these values are realized in the form of modeling with the help of equations given in Chapter 2.

The calculation of I_m, I_{pv} and I_o is shown in Figure4.5, 4.6 and 4.7 respectively.

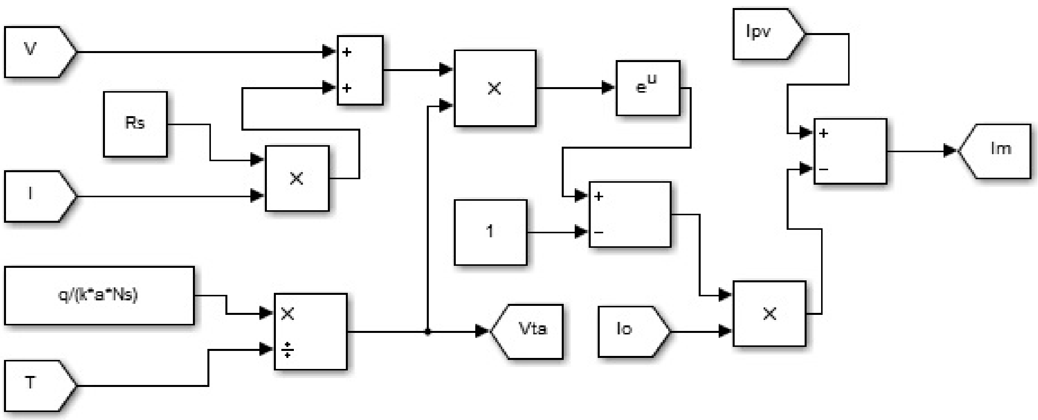

Figure 4.5: Calculation of I_m

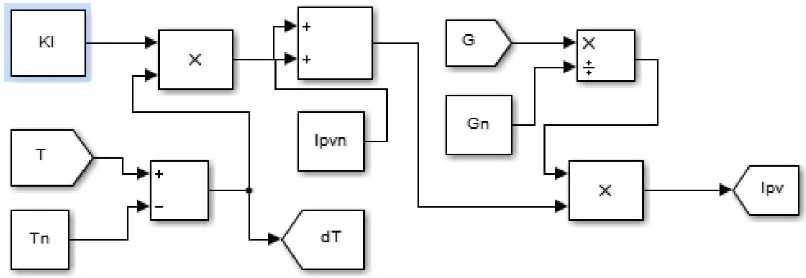

Figure 4.6: Calculation of I_{pv}

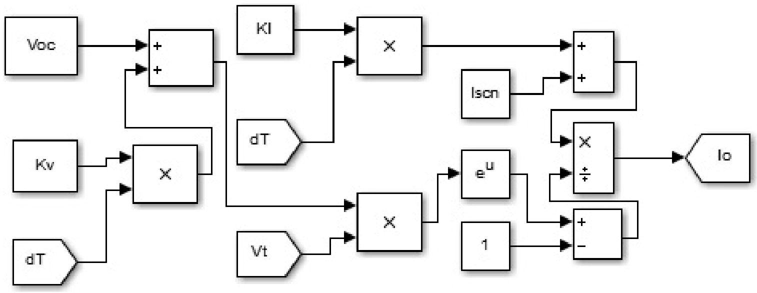

Figure 4.7: Calculation of I_{pv}

The specifications of solar PV array are given below in Table 4.1.

Table 4.1: Specifications of solar PV array

PV MODULE	
Short Circuit Current (I_{sc})	8.21 A
Open Circuit Voltage (V_{ocn})	32.9 V
Voltage at Maximum Power V_{mp} (V)	27.96 V
Current at Maximum Power I_{mp} (A)	6.98 A
Solar PV Array	
PV Voltage at MPP (V_{mp})	590 V
PV Power at MPP (P_{mp})	44 kW
PV Current at MPP (I_{mp})	76.11 A
Number of series modules n_s	22
Number of parallel modules n_p	9

I-V and P-V curves

The I-V and P-V Curves obtained from the modeling of the solar PV array in Simulink are shown in Figure 4.8 and 4.9.

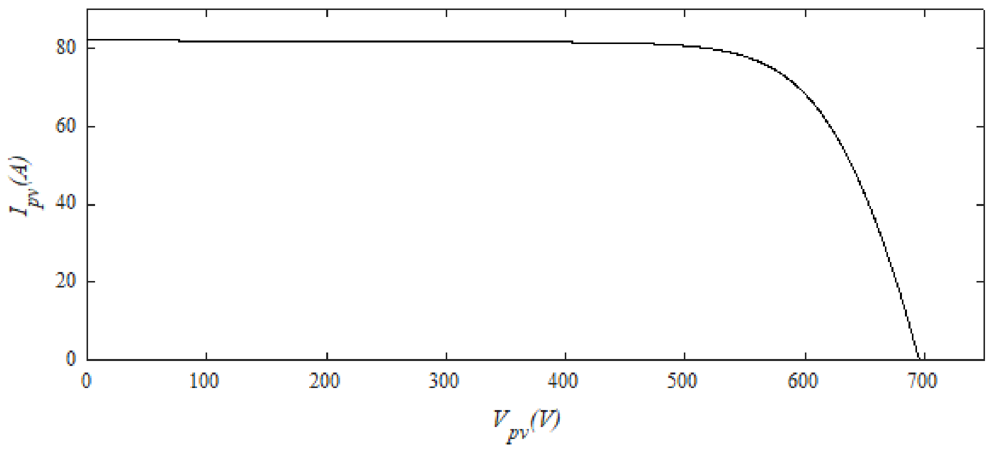

Figure 4.8: I-V curve for PV array

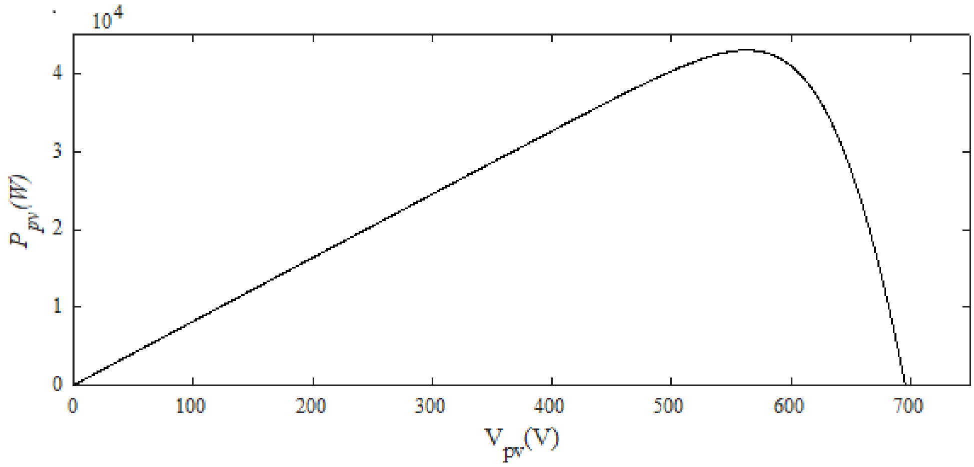

Figure 4.9: P-V curve for PV array

Impact of irradiation on I-V and P-V curves

The short circuit current decreases in direct proportional with the drop-in irradiation [18]. Decrease in irradiation reduces the value of V_{OC} but as it follows a logarithmic relationship so there is not a significant drop which can be seen from the figure shown below as Figure 4.10 and 4.11.

4.2.2 Simulink implementation of DC-DC boost converter

Figure 4.12 illustrates the Simulink modeling of DC-DC boost converter. The value of boost inductor L_b is calculated as per Equation (3.14). P&O MPPT technique is used which generates the pulses for the switching of IGBT used in converter. To control the switching of boost converter control signal is required which is generated by MPPT whose input signals are taken

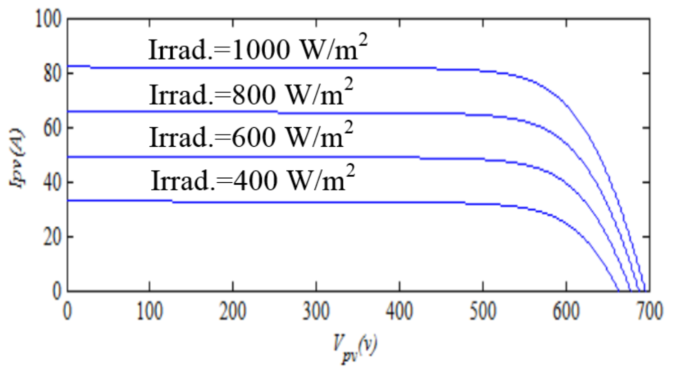

Figure 4.10: IV Curve for varying irradiation when temperature is kept constant at 25^oC

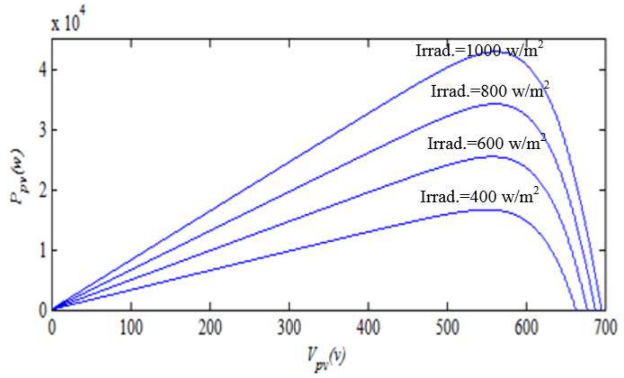

Figure 4.11: PV Curve for varying irradiation when temperature is kept constant at 25^oC

as the ouput current and voltage of PV array. Figure 4.13 represents the output voltage of boost converter in which settles at 728V after few transients.

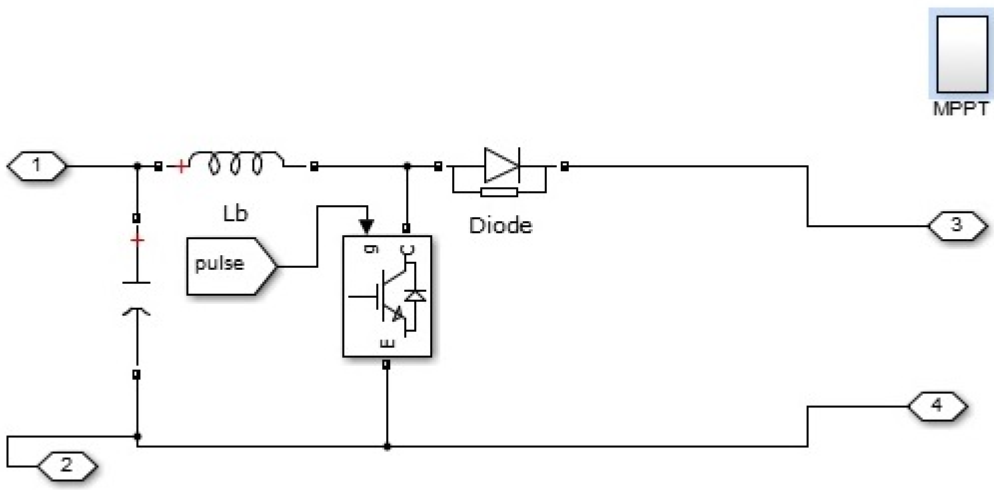

Figure 4.12: Implementaion of DC-DC boost converter

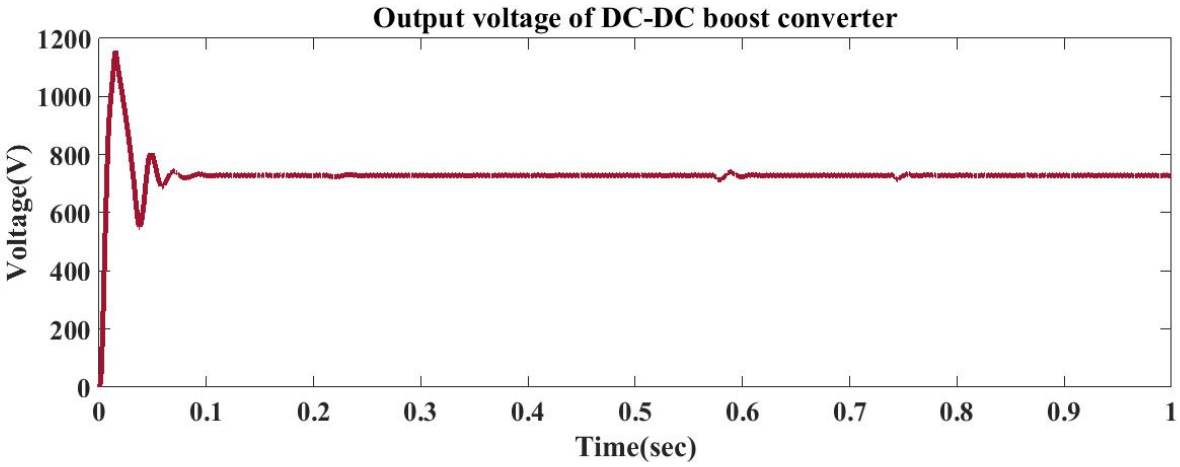

Figure 4.13: Boost converter output voltage

4.2.3 Simulink Implementation of three phase VSI using SPWM

The output of DC-DC boost converter is fed to VSI. In grid connected PV system constant DC voltage is fed as input to inverter which comes from the power produced by the PV array. The SPWM control used in VSI is shown in Figure 4.14. Sinusoidal reference signals are compared with high frequency triangular signal so as to generate control signals for the switches of VSI.

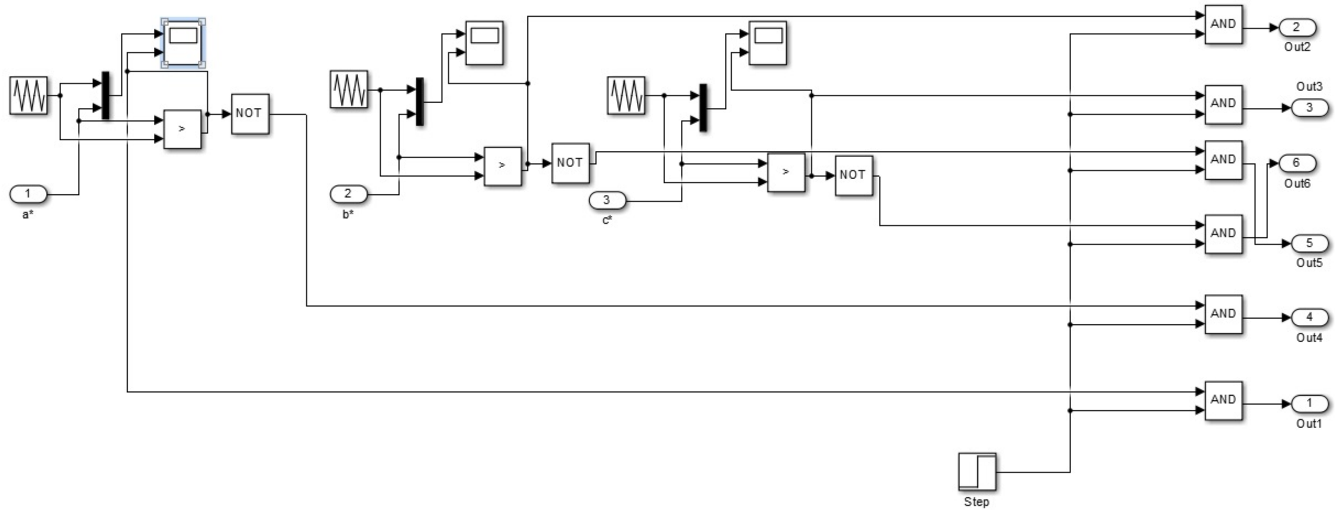

Figure 4.14: SPWM technique for VSI

Chapter 5

Reactive Power Compensation using PV Inverter

5.1 Introduction

The increasing number of distributed generation systems in the existing power system has given rise to many power quality issues that need to be handled in a way to maintain the system parameters within the limits described by the IEEE Standard [3]. Among various parameters, reactive power is an ubiquitous, important and complex feature of the power system. The power which oscillates between the load and the source is called as reactive power. It comes into the picture due to the presence of inductive and capacitive loads in a system. Due to the significant number of these loads in the system, compensation of reactive power has become vital. Most important challenges presented by reactive power are voltage fluctuations and overloading of transmission lines. To avoid the collapse of the entire grid due to voltage fluctuations as a result of excessive reactive power and due to insufficient reactive power, management of reactive power is necessary which means that reactive power must be produced or absorbed locally. Traditionally, the compensators used were mechanically switched inductor and capacitor banks which were replaced by thyristor switched capacitors and flexible AC transmission system (FACTS). The transmission of reactive power over long distance is a challenging task so its localized production is a beneficial choice. One such localized control is with use of inverters coupled with the PV system to provide the reactive power compensation.

5.2 Results and Discussion

5.2.1 Real/Reactive power controller

The gate pulses are blocked intially for real/reactive power controller. The time upto which the gate pulses are zero, line current is zero and average real and reactive power is not exchanged. The values of reference commands are given in Table 5.1

Table 5.1: Values of reference commands of real power and reactive power

Time(sec)	$P_{sref}(kW)$	$Q_{sref}(kVAr)$
t= 0 to 0.15	0	0
t= 0.15 to 0.25	1000	0
t= 0.25 to 0.5	-1000	1000

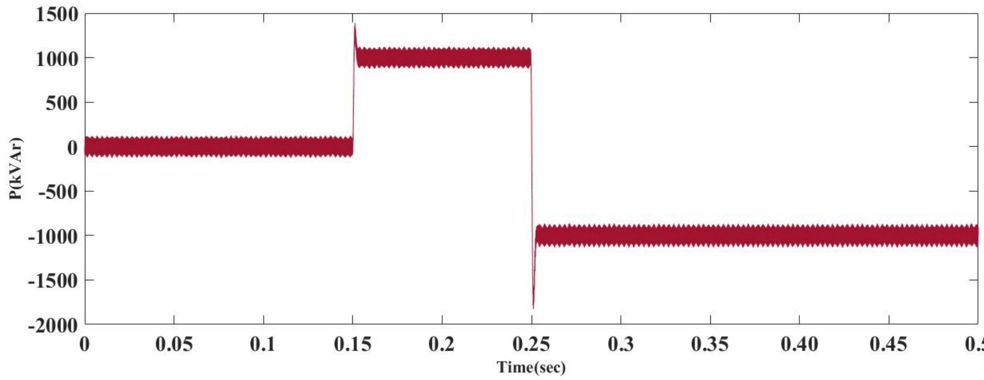

Figure 5.1: Dynamic response of active power

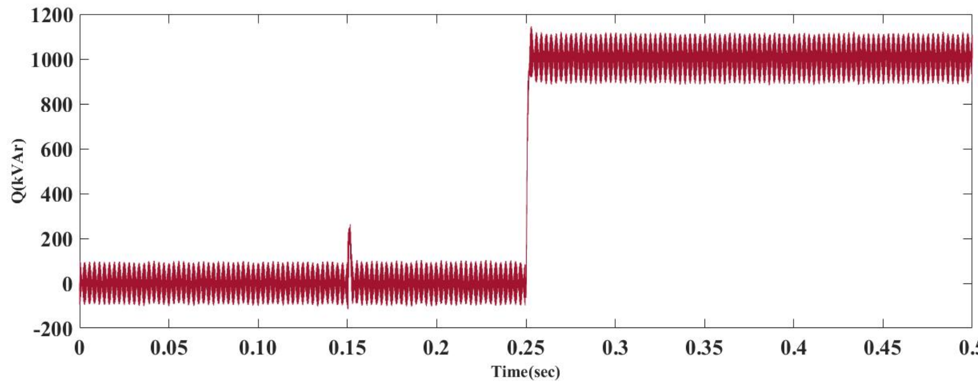

Figure 5.2: Dynamic response of reactive power

Figure 5.1,5.2 and 5.3shows the dynamic response of active power and reactive power. It s clearly indicated that P_s and Q_s follow their reference commands. Some ripples in instantaneous values of active power (P_s), reactive power (Q_s), a-phase of grid voltage (V_{sa}) and

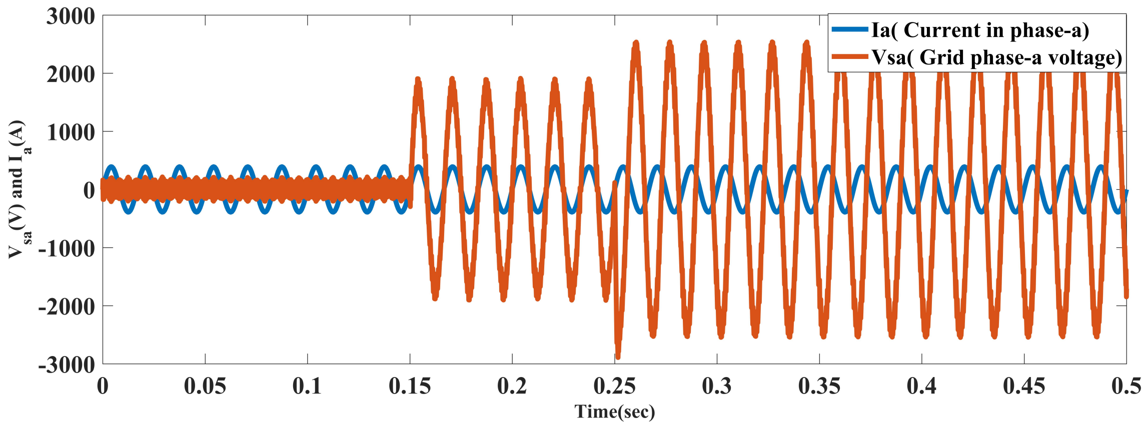

Figure 5.3: Dynamic response of active power and reactive power reflected in the form of voltage and current

a-phase of VSC current (I_a) are because of PWM switching harmonics. P_s and Q_s are not properly decoupled because for their control to be perfectly decoupled, i_α and i_β should follow their reference commands generated from Equation (4.1) and (4.2) is due to limited bandwidth of closed loop system. Figure 5.3 illustrates that i_a is

in phase with V_s, when (P_s, Q_s) = (0 MW, 0 MVAr);

lagging 180^o by V_s, when (P_s, Q_s) = (1 MW, 0M VAr);

lagging by V_s, when (P_s ,Q_s) = (1 MW, 1 MVAr)

5.2.2 Reactive power control in grid connected PV system

The schematic diagram of grid integrated PV system which has been realized with the help of MATLAB/Simulink is shown in Figure 5.4. A 50 kW solar PV system is developed with the help of MATLAB/Simulink. A non- linear load is considered for the system. The behaviour of the PV system is analyzed at steady state and dynamic condition.

Behaviour of solar PV system at balanced load condition

Simulation is performed to analyze the performance of PV array and maximum power point control technique. Solar array of 50 kW is designed and tested for irradiance = 1000 W/m^2 and temperature = 25^{o}C. RL load is considered where the value is r = 12.54 ohm and L = 0.1 Henry. Figure 5.5 and 5.6 represent the grid voltage (V_s) and grid current (I_s). The value of grid voltage is 348 V and that of grid current is 53.28 A. As seen from the plots grid currents are in phase opposition with the grid voltages which means that the reactive power drawn from the grid is zero but non-linear load requires the reactive power which is fed by the PV inverter.

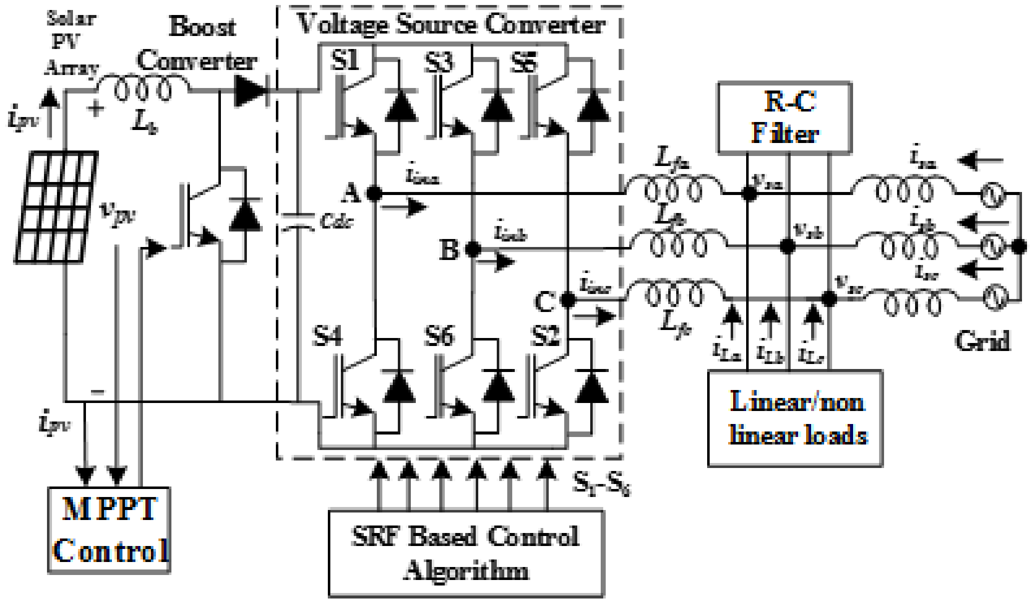

Figure 5.4: Schematic diagram of the implemented grid connected PV system

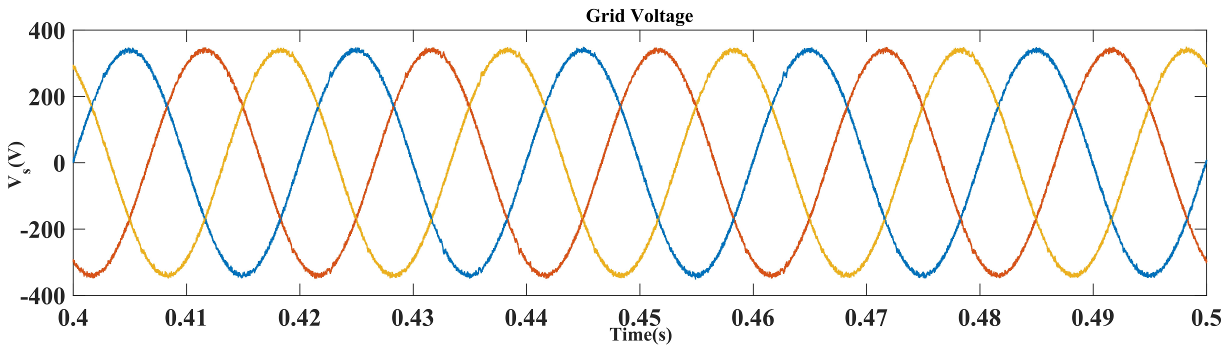

Figure 5.5: Grid voltage at steady state condition under balanced load condition

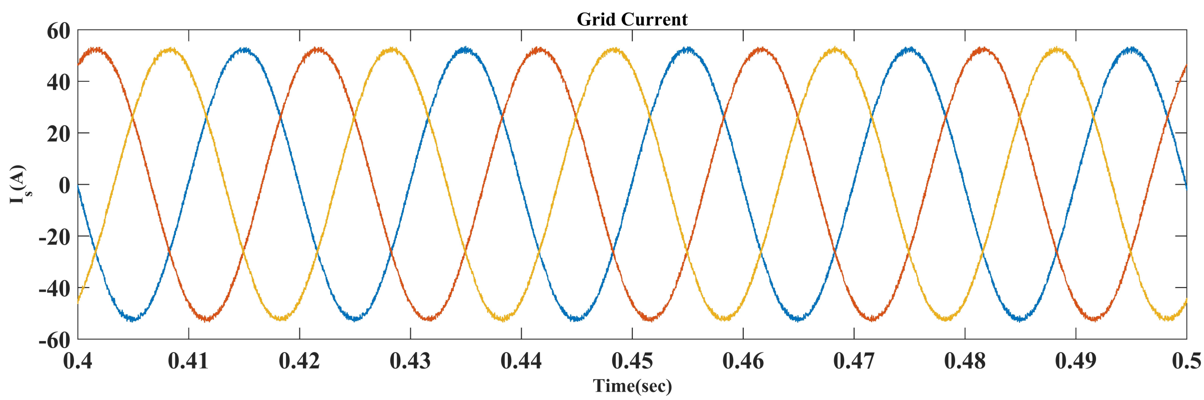

Figure 5.6: Grid current at steady state condition under balanced load condition

The active power is fed to the grid at unity power factor which can be clearly seen from the waveshapes of grid voltage and grid current. The DC-link voltage which is equal to the output of DC-DC boost converter is maintained at 729 V which is clearly indicated in Figure 5.7.

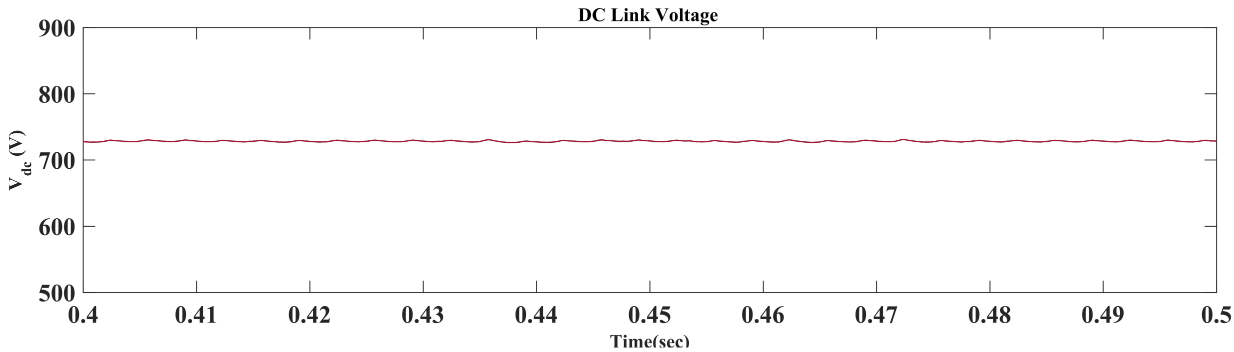

Figure 5.7: DC link voltage under balanced load condition

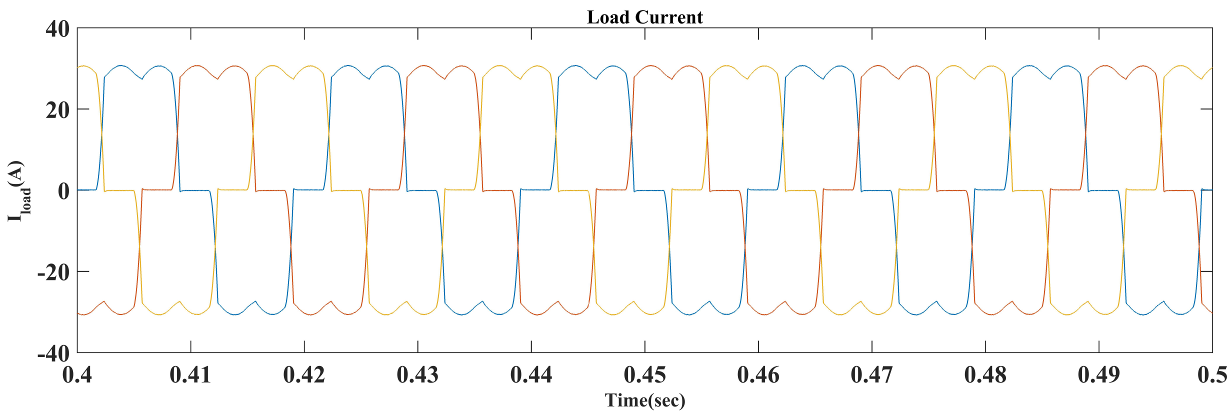

Figure 5.8: Load current under balanced load condition

In the modeling of the system non-linear load is used due to which load current comes out to be quasi-square in nature whose value is 30.7 A as shown in Figure 5.8.

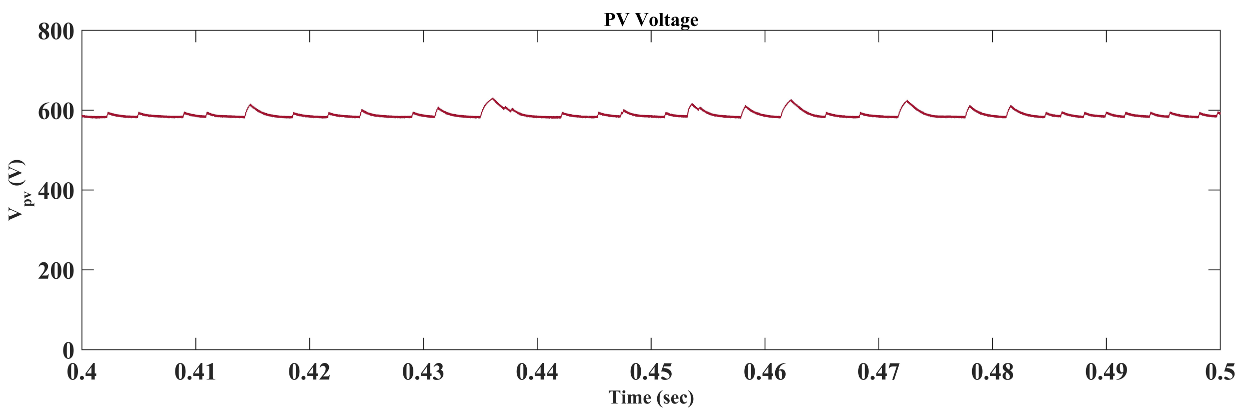

Figure 5.9: PV Volatge under balanced load condition

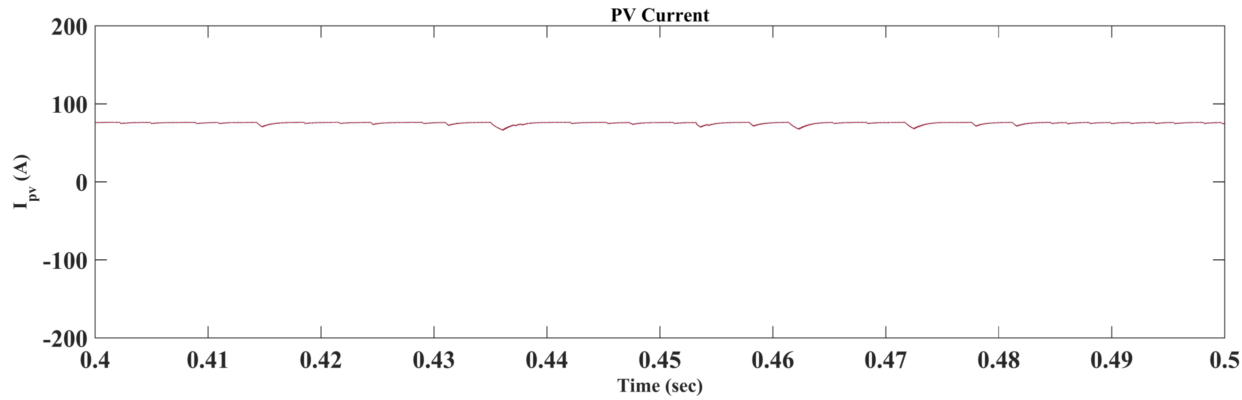

Figure 5.10: PV Current under balanced load condition

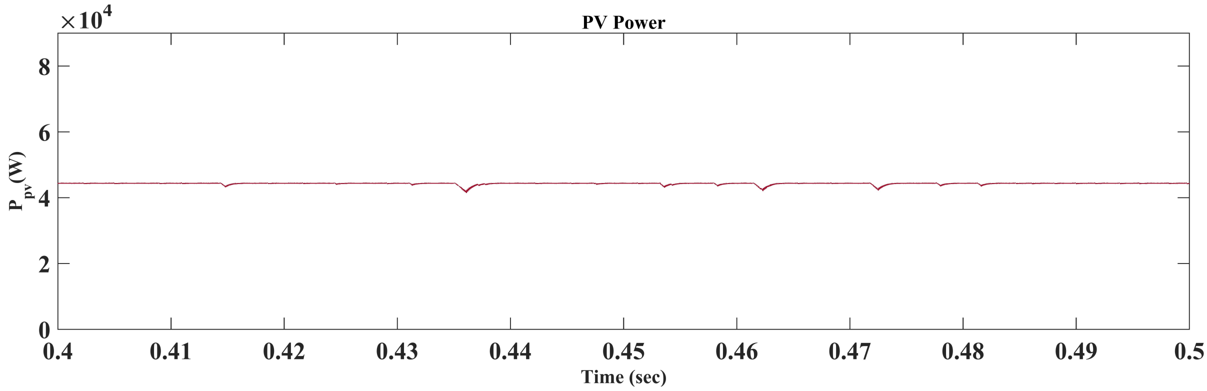

Figure 5.11: PV Power under balanced load condition

The PV voltage is represented in Figure 5.9 is 588 V. PV current is shown in Figure 5.10 which has value equal to 76.33 A and PV power is shown in Figure 5.11 whose value is 44.5 kW.

5.2.3 Dynamic behaviour of the PV system when load is increased by 50%

Modeling of grid connected PV system is performed to analyze the behaviour of PV array. In this case the load is increased by 50% i.e. it becomes one and half times the initial load. The temperature and irradiance are kept same. The value of load resistance r = 18.75 ohm. The grid current is in phase opposition with grid voltage as clear from Figure 5.12 and 5.13. There is no effect on the grid voltage with the increase in the value of load resistance. The value of grid voltage is 348 V. The grid current decreases with the increase in load as the power supplied by the PV array is fixed which means with the increase in load, load current increases which eventually means that the power supplied to the grid decreases which is clearly indicated with the decreased value of grid current and its value is 37.33 A.

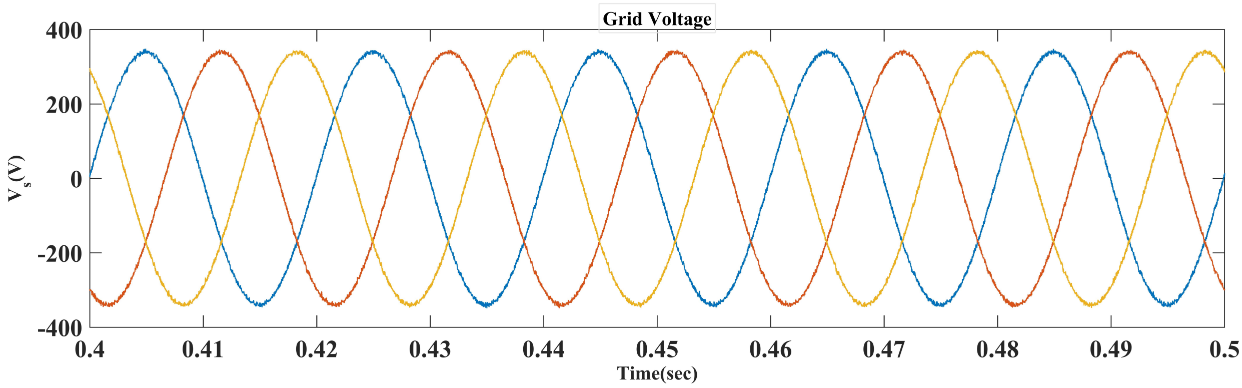

Figure 5.12: Grid voltage at steady state condition under balanced load condition

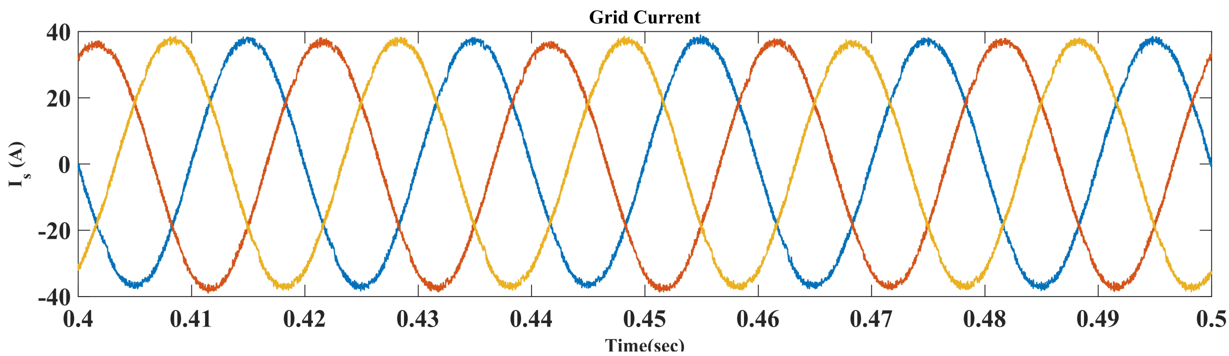

Figure 5.13: Grid current at steady state condition under balanced load condition

The dc link voltage that is equal to the output of DC-DC boost converter has no change and is maintained at 729 V which is clearly shown in Figure 5.14

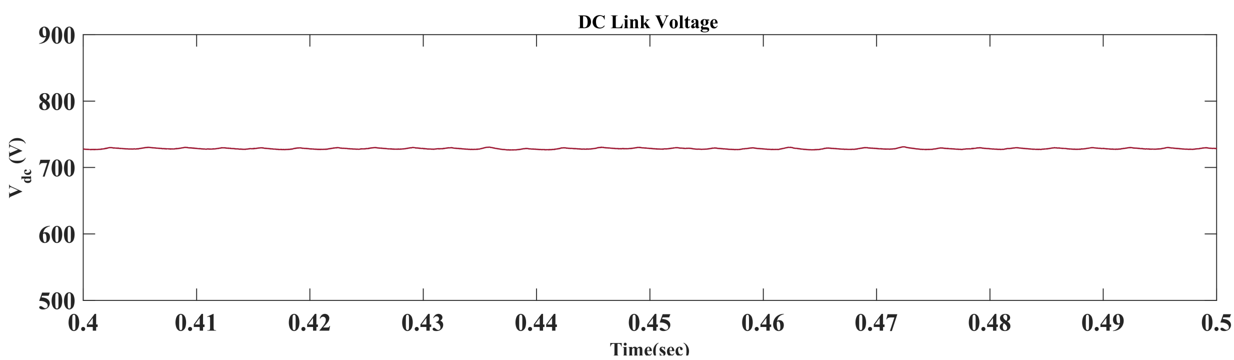

Figure 5.14: DC link voltage under balanced load condition

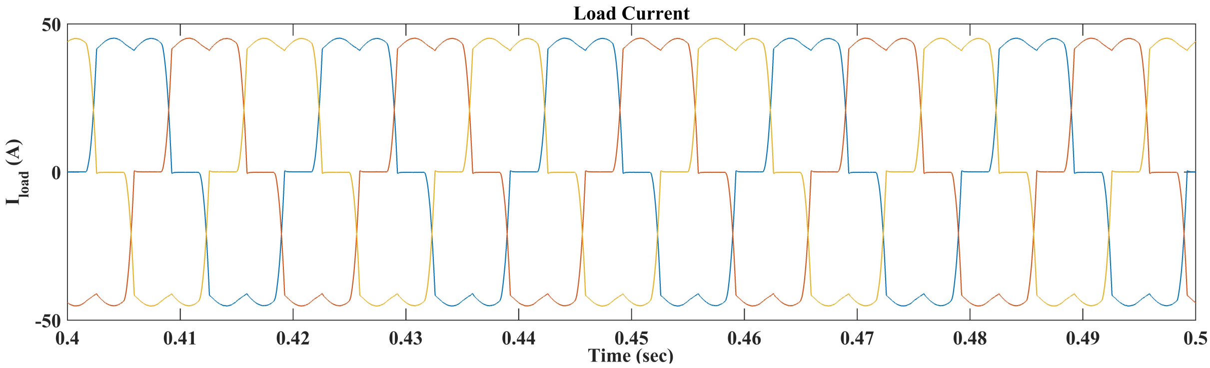

Figure 5.15: Load current under balanced load condition

In the modeling of this system non-linear load is considered because of which load current comes out to be quasi-square. The value of load current increases due to increase in the load resistance. The value of load current is 45.18 A as shown in Figure 5.15.

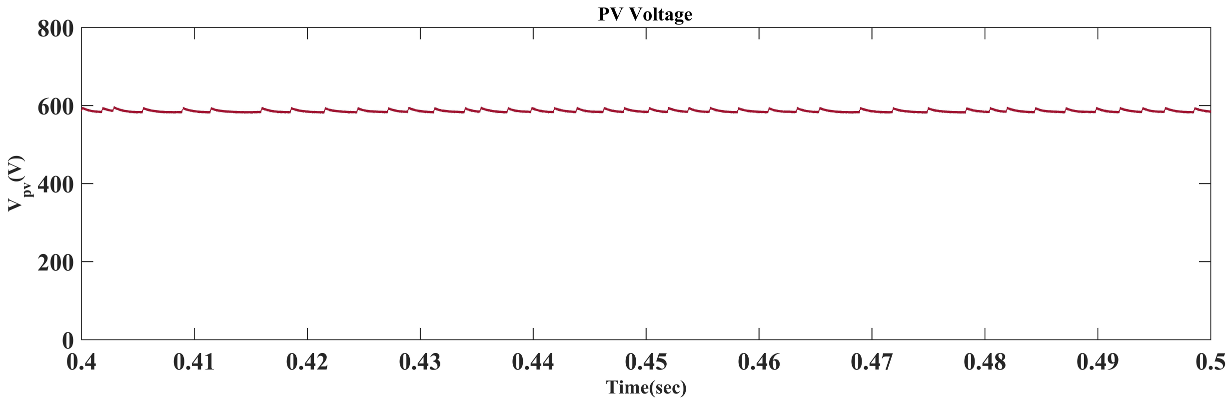

Figure 5.16: PV Volatge under balanced load condition

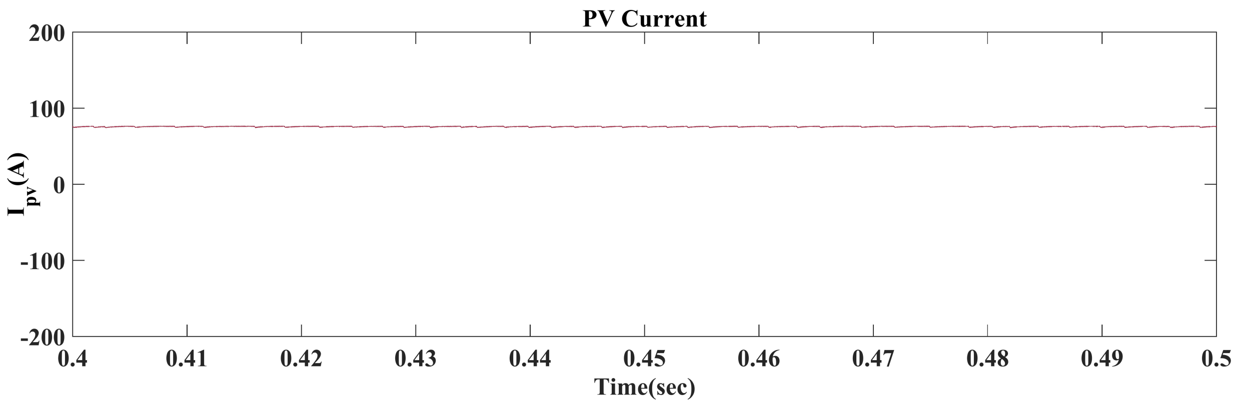

Figure 5.17: PV Current under balanced load condition

The PV voltage represented in Figure 5.16 does not change with increase in load as the ouput of PV depends on temperature and irradiance not on the load. PV current is shown in Figure

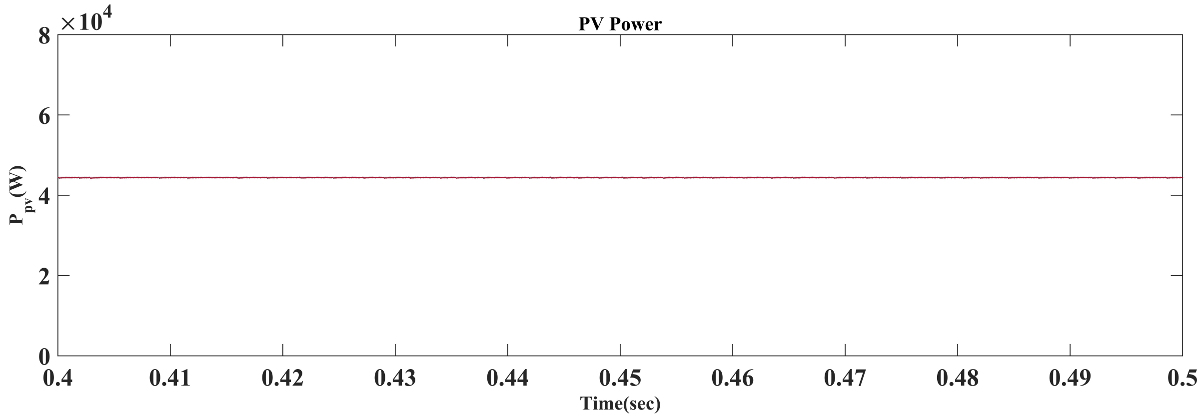

Figure 5.18: PV Power under balanced non linear load

5.17 is maintained at 76.2 A and PV power is shown in Figure 5.18 and has value equal to 44.5 kW.

5.2.4 Harmonic analysis

The harmonic analysis of the grid voltage, grid current is carried out using Fast Fourier Transform (FFT) analysis to check whether the grid parameters especially the grid current are within IEEE standards or not. FFT analysis is performed to make sure whether the grid connected PV system maintains the power quality limits or not.

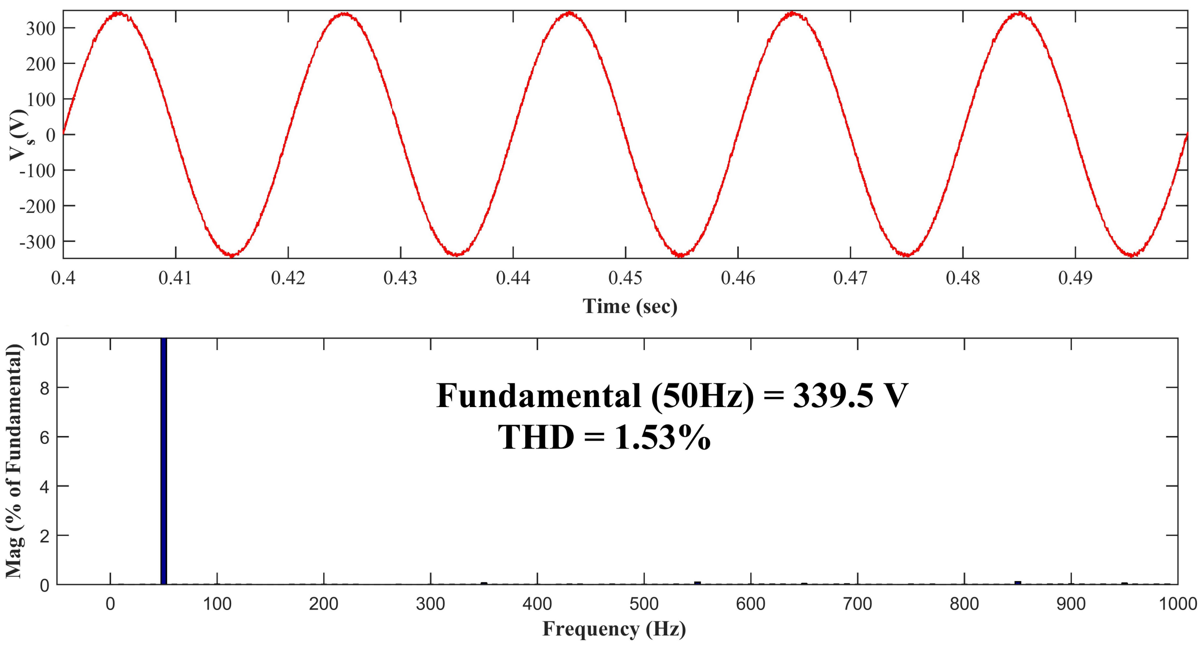

Figure 5.19: Harmonic analysis of grid voltage

Figure 5.19, 5.20 and 5.21 represent the harmonic analysis of grid voltage, grid current and

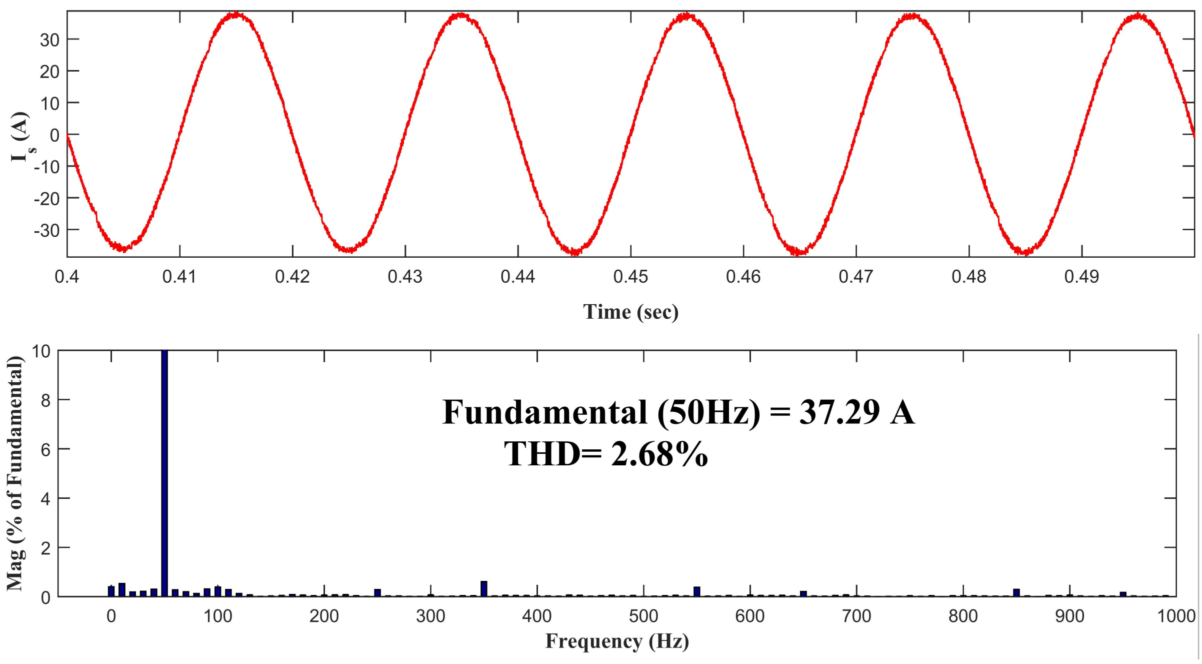

Figure 5.20: Harmonic analysis of grid current

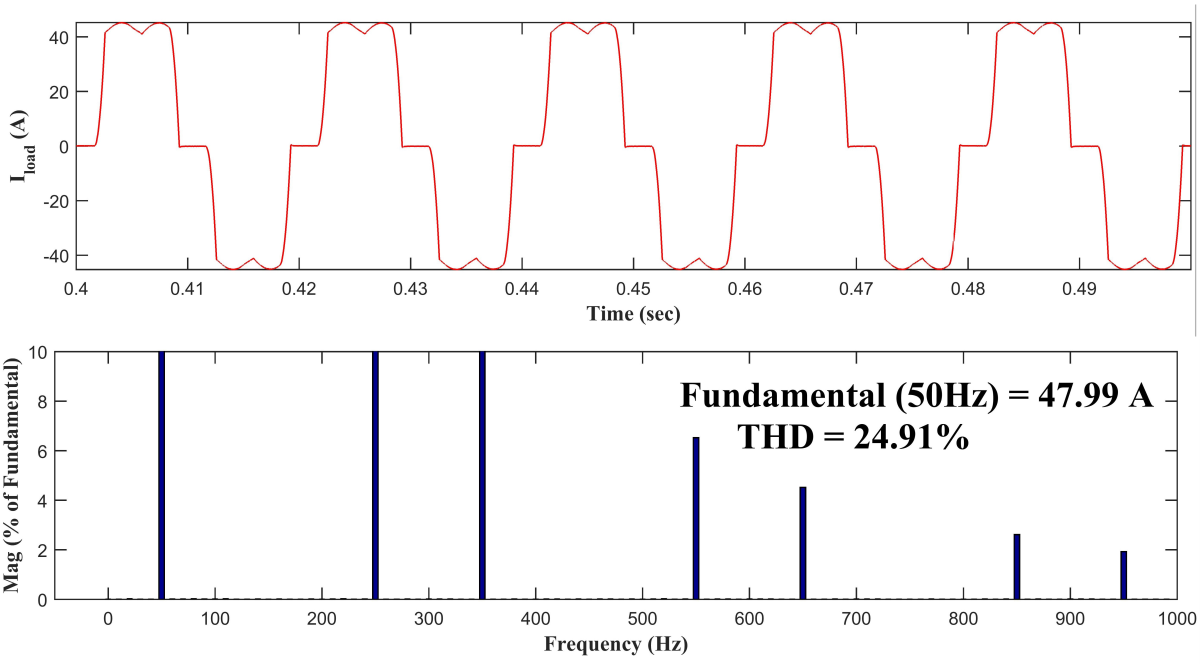

Figure 5.21: Harmonic analysis of load current

load current respectively. From the value of THD of grid current it is clear that THD of grid current on the application of non-linear load is within IEEE Std 519 i.e. less than 5% which clearly proves that although the non-linear load with high value of THD as indicated by Figure 5.21 is high but still it does not have effect on the grid parameters which is sufficient to say that the reactive power required by the load is provided by photovoltaic inverter and reactive power is controlled effectively with the control scheme used in the system such that grid connected PV system works efficiently.

5.2.5 Dynamic behaviour of the PV system under unbalanced load condition

For unbalancing the connected non-linear load, phase a of the load is disconnected for the interval 0.4 sec to 0.5 sec with the help of circuit breaker which operated for the this duration.

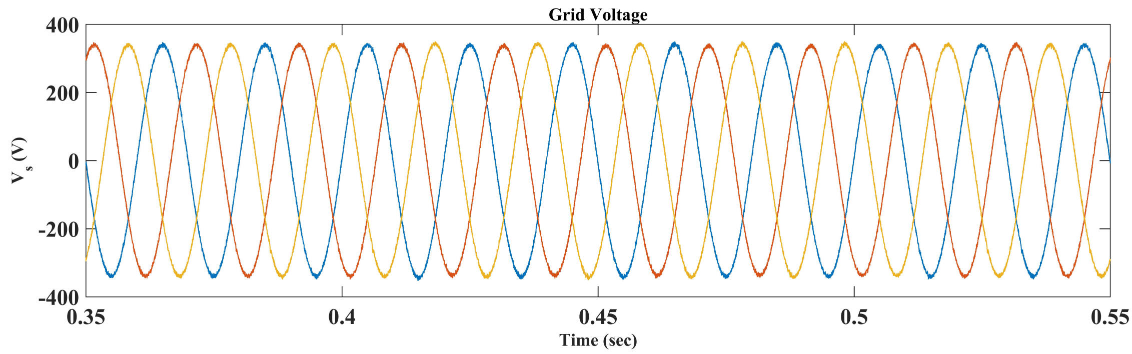

Figure 5.22: Grid voltage under unbalanced load condition

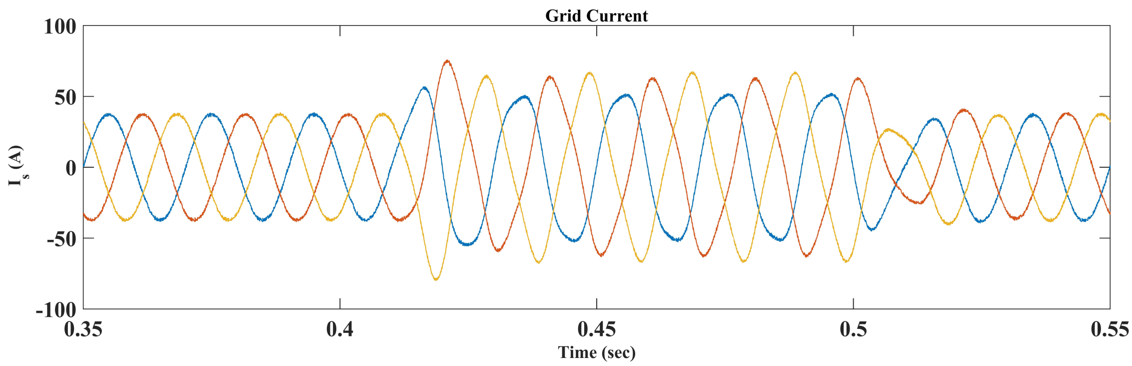

Figure 5.23: Grid current under unbalanced load condition

When the phase a of the connected non-linear load is removed from 0.4 s to 0.5 s by operating the breaker, it is seen that solar power P_{PV} is not changed ie. same as it was at steady state as it is dependent on the solar conditions and array specifications and does not change with load as shown in Figure 5.28.The grid voltage represented by Figure5.22 is not effected. The value of the grid current has increased as seen in the Figure 5.23 which means that power supplied to the grid has increased.The DC link voltage is well maintained as it was at steady state as shown in Figure 5.24. The load current, PV voltage and PV current are shown in Figure 5.25, 5.26 and 5.27 respectively.

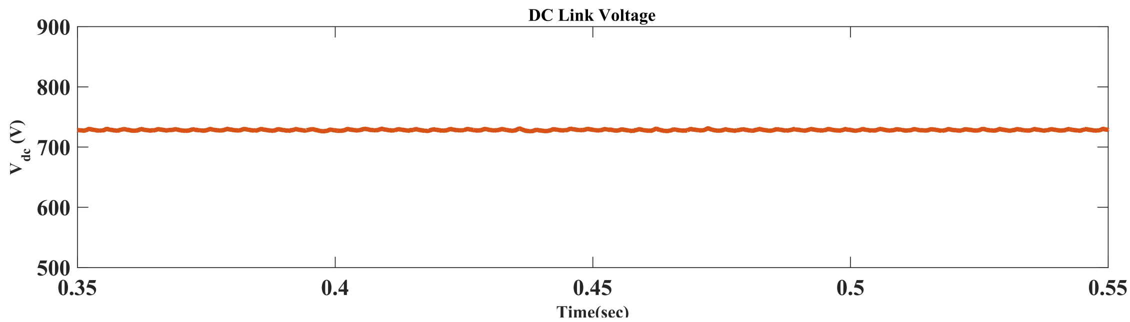

Figure 5.24: DC link voltage under unbalanced load condition

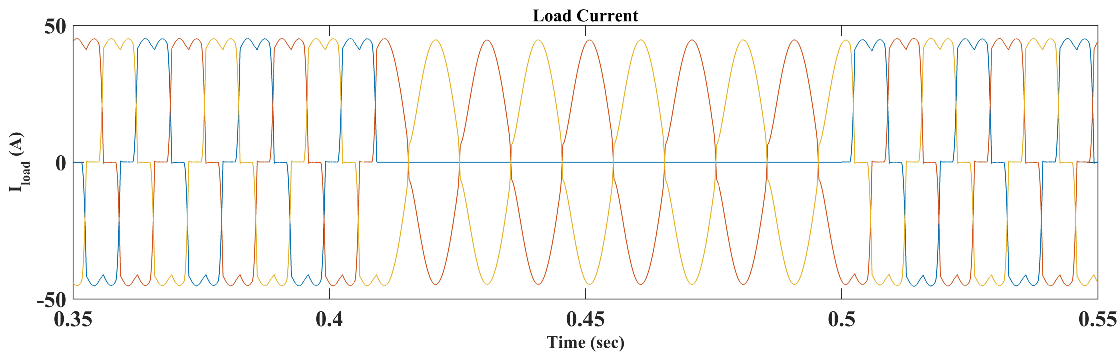

Figure 5.25: Load current under unbalanced load condition

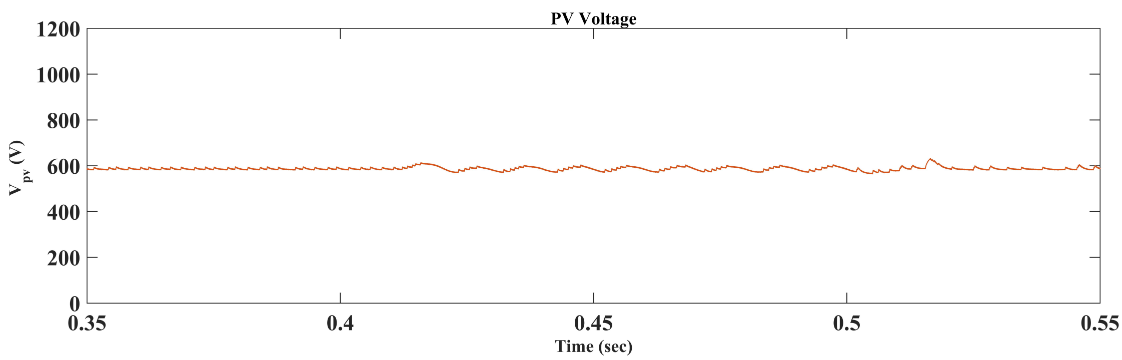

Figure 5.26: PV Voltage under unbalanced load condition

From all the results discussed above it is clearly understood that MPPT technique is applied correctly as during the changes in load also the value of PV voltage, PV current and PV power remains constant which indicates that PV array is working efficiently. The SRF control scheme is implemented properly which is clearly understood by the fact that DC link voltage is maintained at a constant value. At normal value of load, increased value of load or at unbalanced load condition, the power factor of the grid is maintained at 1 which can be clearly seen from the grid voltage and grid current waveforms. Hence, the reactive power is controlled in the system. The system parameters are not disturbed and the power factor does not get affected

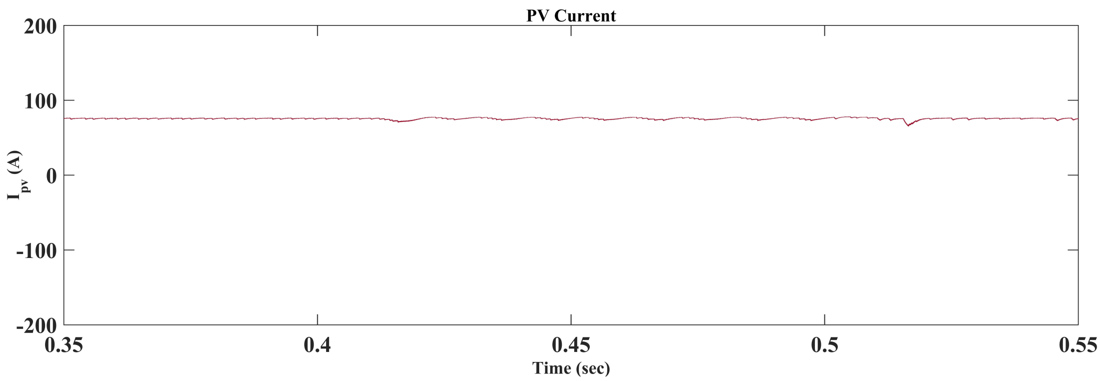

Figure 5.27: PV Current under unbalanced load condition

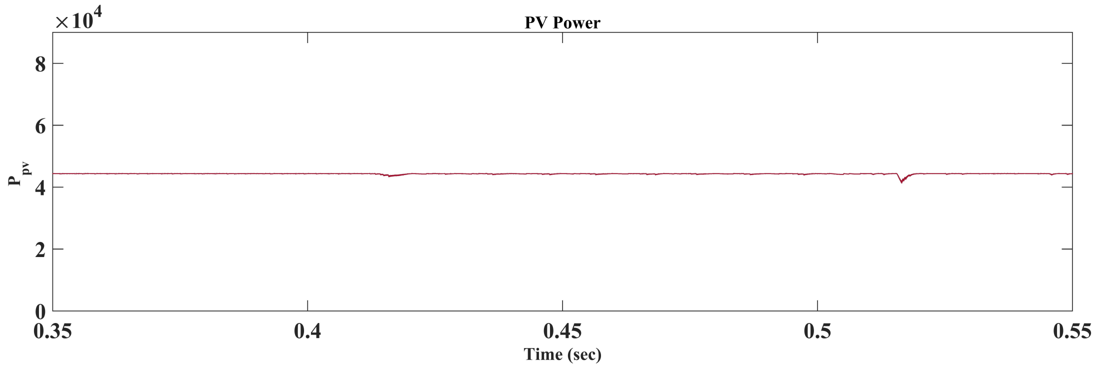

Figure 5.28: PV Power under unbalanced load condition

even when the load demands reactive power.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

A grid connected PV system is realized with the help of MATLAB/Simulink. It includes the modeling of the PV array as well as the power conditioning system. The SRF based control scheme is used in the system to control the switching of VSI and eventually to keep the system parameters in limits and to compensate the reactive power requirement of the load by PV inverter. To get the maximum power from the PV array, P&O MPPT technique is used. The reactive power required by the non-linear load is supplied by the PV inverter as grid current is in phase opposition to the grid current. Power factor is maintained at unity hence, the power quality of the system is not affected even on the application of nonlinear loads. The THD of the grid voltage and current is also maintained within the limits (IEEE-519).

6.2 Future Scope

- The grid integrated PV System developed in this work can be further improved and reconfigured by adding a storage battery so that it can work as a microgrid.
- The system developed using Simulink works only in grid connected mode but not as a standalone system. Some control technique can be used so as to make transition from grid connected mode to standalone mode and again to the grid connected mode. Controller can be designed for the automatic operation or transition from one mode to the other as per the requirement of the system.

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