CONTROL OF GRID CONNECTED SOLAR PHOTOVOLTAIC SYSTEM INCORPORATING LOAD HARMONIC COMPENSATION

A DISSERTATION

Submitted in partial fulfillment of the requirement for the degree of

Master of Technology

in

Electrical Engineering (Power Systems)

by

Neeraj Meena

(2K12/PSY/10)

Under the esteemed guidance of

Dr. Mukhtiar Singh

Electrical Engineering Department

Delhi Technological University

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Delhi- 110042

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CERTIFICATE

I, **Neeraj Meena**, Roll No. 2K12/PSY/10 student of **M. Tech. (Power System)**, hereby declare that the dissertation/project titled **"Control Of Grid Connected Solar Photovoltaic System Incorporating Load Harmonic Compensation"** under the supervision of Dr. Mukhtiar Singh, Associate Professor, Department of Electrical Engineering Department, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi

Date: 31.07.2014

NEERAJ MEENA

Dr. MUKHTIAR SINGH

SUPERVISOR

Associate Professor

Electrical Engineering Department

Delhi Technological University

Bawana Road, Delhi-110042

ACKNOWLEDGEMENT

I would like to thank my honourable guide Dr. MUKHTIAR SINGH, Associate Professor, Department of Electrical Engineering, Delhi Technological University (formerly Delhi College of Engineering). It would have never been possible for me to take this project to completion without his innovative ideas and his relentless support, encouragement and patience. I consider myself fortunate to have had a chance to work under his supervision. In spite of his hectic schedule he was always approachable and took his time to discuss my problems and give his advice and encouragement.

I would like to express my deep gratitude to Prof. Madhusudan Singh, Head, Department of Electrical Engineering for providing his support during my project.

I am also very thankful to the entire faculty and staff members of the electrical engineering department for their help and cooperation.

I wish to thank Ph.D scholars Mr. Ashutosh Trivadi for the invaluable knowledge they imparted to me during course work.

I would also like to thank my batch-mates and friends who encouraged and helped me in completing the thesis work.

Finally, I express my deep sincere thanks to my Parents my brother and sister who motivated and encouraged me for higher studies, without which it wouldn't have been possible.

Date: 31 July, 2014

NEERAJ MEENA

Roll no. 2K12/PSY/10

M.tech (Power System)

Delhi Technological University, Delhi

DECLARATION

I, hereby declare that the work being presented in this Project Report entitled **“Control of Grid Connected Solar Photovoltaic System Incorporating Load Harmonic Compensation”** is an original piece of work and an authentic report of our own work carried out during the period of 4th Semester as a part of our major project.

The model developed and results presented in this report is an outcome of the work carried out during the above said period and is also compiled as thesis for my Major Project for completing the requirements of Master‘s Degree of Examination in Power System Engineering, as per Delhi Technological University curriculum.

Neeraj Meena

Roll no. 2k12/PSY/10

M.tech (Power Systems)

Department of Electrical Engineering

Delhi Technological University, Delhi.

ABSTRACT

The demand for energy worldwide is increasing rapidly year by year and scientist all over the world is looking for the alternative source of energy. Among, various available renewable energy sources, solar photovoltaic (SPV) energy is considered to be most reliable, environment friendly, pollution free and unlimited in nature. The solar energy is directly converted into electrical energy by solar cell/ module. The characteristics of PV depend upon irradiation and temperature. The temperature and the irradiation of the solar cell depend on the atmospheric conditions. Hence, it is essential to track the maximum power point (MPP) in any conditions to assure that the maximum available power is obtained from the PV panel. When PV is interfaced to the grid power quality problems may arise due to use of power electronic devices in the form of voltage source converter (VSC) for coupling. In this proposed work solar PV is modeled using single diode electrical equivalent circuit of solar cell and the characteristics of PV module are generated. The Perturbation and observation (P&O) technique is modeled and implemented. The maximum power point (MPP) is obtained using MPPT and dc-dc boost converter. Complete evacuation of generated power from PV source is done using maximum power tracking. This improves the overall system efficiency. Moreover, the Grid side inverter is utilized to compensate the load current harmonics and load reactive power demand. This enables the grid to always act at unity power factor. Solar PV system is controlled and synchronized to grid using synchronous reference frame theory (SRFT) algorithm. A variety of linear/non-linear load conditions are considered.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREBIATIONS

SPVA	Solar Photovoltaic Array
DC	Direct Current
AC	Alternating current
MPT	Maximum Power Tracking
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
P&O	Perturbation and Observation
IC	Incremental Conductance
SRFT	Synchronous Reference Frame Theory
DER	Distributed Energy Resource
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
DG	Distributed Generation
PWM	Pulse Width Modulation
HCC	Hysteresis Current Control
IGBT	Insulated Gate Bipolar Transistor
KVA	Kilo Volt Ampere
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
PI	Proportional Plus Integral
PLL	Phase Locked Loop
PWM-VSI	Pulse Width Modulated Voltage Source Inverter

CHAPTER 1
INTRODUCTION

1.1 GENERAL:

Energy plays an important role in our daily life activities. The ability or the capacity to do work is defined as Energy. All the energy in oil, gas, and coal originally came from the sun, captured through photosynthesis. Most of the energy we use comes from fossil fuels. Coal is one of the fossil fuels. Due to the use of fossil fuels, several problems such as global warming and greenhouse effect are increasing day by day and will have serious consequences on the whole world. Moreover, the cost of fossil fuel has been increasing very rapidly. To handle the problem of increasing demand and diminishing conventional energy sources, each country is focusing on alternate source of energy or renewable energy sources**.** A renewable energy system convert the energy found in sunlight, water, wind, geothermal heat, or biomass into a form, which we can use in the form of heat or electricity. The majority of the renewable energy comes either directly or indirectly from sun and wind and can never be fatigued, and therefore they are called renewable. Hence the demand for renewable energy sources increases as it is environmental friendly and pollution free which reduces the greenhouse effect. Approximately 16% of global energy consumption in the world is met from renewable energy resources, with 10% of all energy from traditional biomass, and 3.4% from hydro-electricity. New renewable energy sources like small hydro, modern biomass, wind, solar, geothermal, and biofuels account for another 3% and are growing very rapidly. Amongst the above mentioned sources of energy there has been a lot of development in the technology for harnessing energy from the sunlight. In this chapter, India's power at a glance, Renewable energy status, Solar Energy potential in World and India and the types of material used for solar cell are discussed.

1.2 INDIA'S POWER AT A GLANCE:

The installed power generation capacity of India as on June 30, 2014 was 249488 MW. The total Demand for electricity in India is expected to cross 950000 MW by 2030. The total power installed capacity of India is shown in figure 1.1. The total installed Renewable Power Capacity of India as on 31st March, 2014 is shown in figure 1.2.

Power Installed Capacity (~249GW)

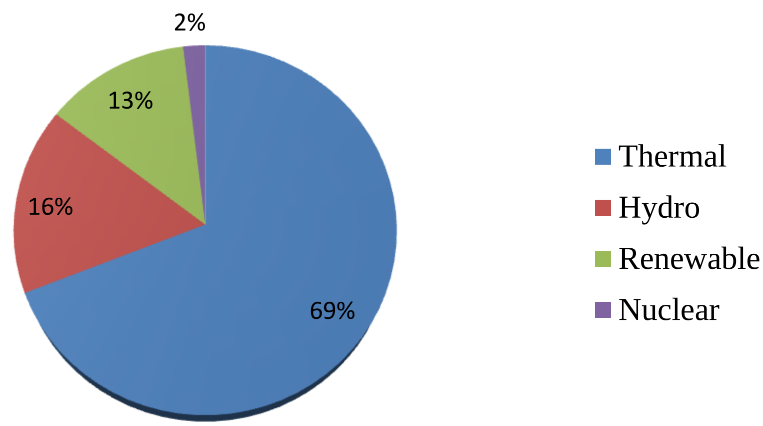

Figure:1.1 Sources of electricity in India by installed capacity

THERMAL	HYDRO	RENEWABLE	NUCLEAR
1,72,286 MW	40,730 MW	31,692 MW	4,780 MW

Installed Renewable Power Capacity (~31GW)

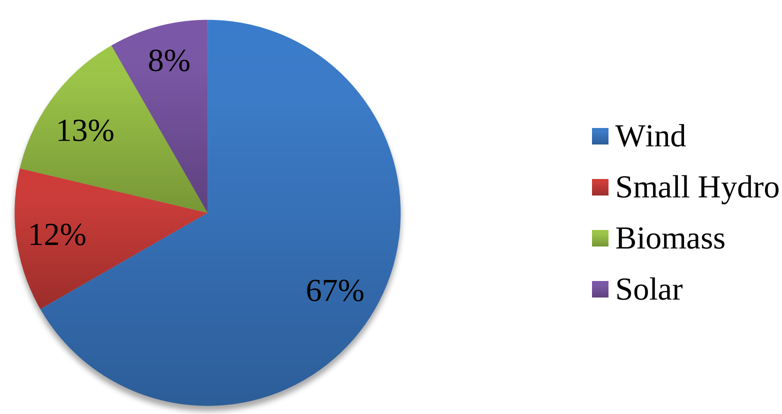

Figure 1.2: Distribution of Renewable Power capacity in India

WIND	SMALL HYDRO	BIOMASS	SOLAR
21,136 MW	3803 MW	4120 MW	2631 MW

1.2.1 Solar Energy Production In Indian States (as on March 2013):

S. No.	States	Megawatt power (MW)	Percentage of total production in India (%)
1	Gujarat	824.09	57.20
2	Rajasthan	442.25	30.69
3	Andhra Pradesh	23.15	1.61
4	Maharashtra	34.5	2.39
5	Tamil Nadu	17.055	1.18
6	Orissa	13	0.90
7	Uttar Pradesh	12.375	0.85
8	Karnataka	14	0.97
9	Punjab	9.325	0.65
10	Haryana	7.8	0.54
11	Uttarakhand	5.05	0.35
12	Chhattisgarh	4	0.28
13	Jharkhand	16	1.11
14	Delhi	2.525	0.17
15	Madhya Pradesh	11.75	0.81
16	West Bengal	2	0.14

Table 1.1:State-wise solar power production for the year 2013

1.3 RENEWABLE ENERGY & SOLAR ENERGY:

Energy is required for our life and economy. As the country develops it needs more energy. Now a days energy is supplied by burning fossil fuels such as coal, diesel. Increased energy demand results in two problems: energy crisis and climate Change (global warming). The worldwide energy demand increases, the energy related green house gases emission increases. It is global challenge to reduce the CO_2 emission and provide clean, sustainable and affordable energy.

Energy saving is one cost effective solution but does not tackle the worldwide increasing energy demand. Using Renewable energy is good option because it provides clean and green energy, with little or no CO_2 emission. Renewable energy is generated from renewable energy sources such as Solar emission, Wind, Tides, geothermal etc. The major renewable energy technologies are Hydropower, wind power generation, biomass and ocean energy. This energy is used in Power Generation, Rural electrification (off-grid) and as transport fuels. Compared to fossil fuels, renewable energy has many advantages. Firstly, the renewable energy obtained from natural sources so it is sustainable and it will not emit CO_2 gas. So renewable energies tackle the green house effect and also provide sustainable energy. To achieve the renewable energy target, more funds will be provided in research and development of renewable energy.

1.3.1 SOLAR ENERGY:

Solar energy is one of the important source of renewable energy. The sun radiates large amount of energy which is enough to satisfy the need of whole world. Solar energy is used for providing heating, cooling, light and for electricity. One of the important technologies is Photovoltaic (PV) by photoelectric effect the sunlight is directly converted into electricity. In 1839 the Edmond Becquerel found the photoelectric effect accidently while working on solid-state physics. In 1883, Fxitz fabricated the first thin film solar cell. In 1941 oil fabricated silicon PV cell but that was very inefficient. In 1954 Bell labs Chopin, Fuller, Pearson fabricated PV cell with efficiency of 6%. In 1958 PV cell was used as a backup power source in satellite Vanguard-1. This extended the life of satellite for about 6 years. PV generation has following main advantages:

a) It is abundant and sustainable.
b) It is green and clean. The production of PV energy does not produce green house gases hence it is safe. It is pollution free, since manufacturer of PV are committed to minimize pollution during production.
c) PV energy is reliable, since power generation using PV has no moving parts hence it has less maintenance. When PV is used as distributed energy source it reduces the cost of transmission lines and improves grid reliability.
d) It has longer life than other renewable technologies.

However there are few problems when using PV energy: PV energy is dependent on weather condition. It is not available at night. During cloudy weather its efficiency becomes less. Hence PV energy generation is Intermittent and variable.

The cost of large scale PV system installation is high compared to conventional energy systems for same energy production. The research is going on to reduce the installation cost of large scale power generation and to increase the efficiency of PV system.

1.3.2 CONVERSION OF SOLAR TO ELECTRICAL ENERGY:

Solar to electrical energy conversion can be done in two ways: solar thermal and solar photovoltaic.

<u>Solar Thermal:</u> Solar thermal is similar to conventional AC electricity generation by steam turbine excepting that instead of fossil fuel; heat extracted from concentrated solar ray is used to produce steam and apart is stored in thermally insulated tanks for using during intermittency of sunshine or night time.

<u>Solar Photovoltaic:</u> Solar photovoltaic use cells made of silicon or certain types of semiconductor materials which convert the light energy absorbed from incident sunshine into DC electricity. To make up for intermittency and night time storage of the generated electricity into battery is needed.

1.4 SOLAR CELL (PV):-

The phenomenon of conversion of sunlight into electricity is known as the Solar Power Generation and it can be done by two ways-

1. Direct conversion using Solar Photovoltaic cell
2. Indirect method of using Concentrated Solar Power

Solar cells are devices in which sunlight releases electric charges so they can move freely in a semiconductor and ultimately flow through an electric load such as a light bulb or a motor. The phenomenon of producing voltages and currents in this way is known as the Photovoltaic effect. Solar energy has a vast area of application such as electricity generation for distribution, heating water, lighting building, crop drying etc.

1.4.1 Operating Principle:

The basic components of photovoltaic panels are the solar cells and photovoltaic means the direct conversion of sunlight into electricity. The Electromagnetic radiation is converted directly into electrical current by some semiconductors. Semiconductor materials such as silicon (Si), gallium arsenide (GaAs), cadmium telluride (CdTe) or copper indium diselenide (CIS) are used in these solar cells. Sunlight enters the semiconductor and produces an electron and a hole - a negatively charged particle and a positively charged particle, both free to move.

A P-N (positive-negative) junction is formed when a p doped and n doped semiconductor materials are brought together and merges into the same lattice. In case of p-type material atoms have one less valence electron, are known as acceptors and in case of n-type material atoms have one more valence electron, are known as donors.

When we join the two layers of different materials together then n-layer side electrons get diffused to p-side and p-layer side holes get diffused to n-side. Therefore, an electric field is created at both sides which opposes the flow (movement) of carriers and is responsible for potential barrier to further flow of charge carriers. This electric field pulls the carriers i.e. electron and holes to cause the flow of current in one direction. The electric currents caused by this charge collection flow through metal wires to the electric load.

The effect of electric field in the diagram of p-n junction is shown in figure 1.1

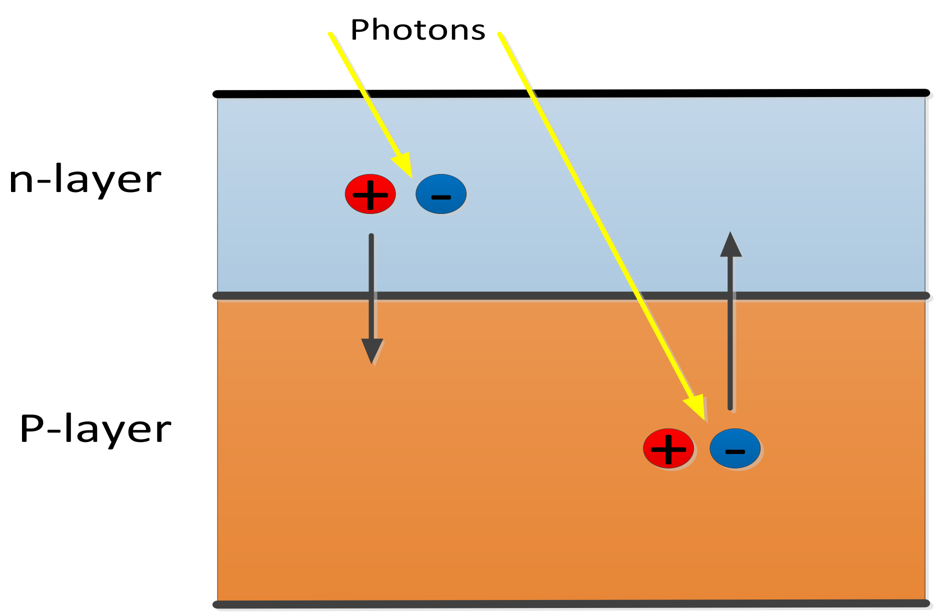

Figure1.3: Solar Cell

If the Solar Cell (p-n semiconductor) is exposed to light, photons are absorbed by the electrons. Some photons reflect from the top surface of the cell and metal fingers. Some photons penetrate in the substrate. Some photons can create an electron-hole pair. The current from the cell may pass directly through the load, or it may be changed first by the power-conditioning equipment to alternating current at voltage and current levels different from those provided by the cell.

Other sub-systems that may also be used include energy storage devices such as batteries, and concentrating lenses or mirrors that focus the sunlight onto a smaller and a less costly semiconductor cell. If concentration is employed, a tracking subsystem may be required to keep the array pointed at the sun throughout the day. The whole process of generation of electric current through absorption of photons due to sunlight is known as Photovoltaic effect and the light generated current depends upon the irradiance and also the temperature of the solar cell.

1.4.2 Types of Solar Cell:

Most semiconductor devices, including solar cells, require thin wafers with a thickness of approximately 0.2 to 0.5 mm. Silicon is only the material that is used for manufacturing solar cells. About 80% of the production is done by the silicon. Also crystal defects on the surface of the silicon slice are significantly lower, reducing the manufacturing cost and increasing the efficiency of the solar cells. The main types of silicon solar cells are the Monocrystalline and polycrystalline silicon solar cells. Amorphous silicon is also a type of silicon but due to its worst efficiency, it is rarely used. We can make new solar cells with the help of copper indium gallium diselenide (CIGS) or cadmium telluride (CdTe).

1.4.2.1 Mono- crystalline silicon:

The most efficient is the Mono-crystalline silicon solar cell. They have been made of wafers sawed from large single-crystal ingots that are obtained from pure molten silicon. The structure of large single crystal wafers are highly ordered because of their uniform and predictable properties. The manufacturing process should be really careful and expensive that occurs at high temperature. The efficiency is around 15-18% of these solar cells and the surface that is required to get 1 kW in STC is about $7m^2$.

1.4.2.2 Polycrystalline silicon:

Polycrystalline silicon cells have been also made of wafers sawed from large single crystals that are obtained from pure molten silicon. However, the structure of the crystal is random. It crystallizes and produces an irregular structure, crystals of random sizes, shapes and orientation when the silicon cools. However, the manufacturing process is less expensive, so the lower efficiency is compensated in some way. The surface that is required to get 1 kW in STC is about $8m^2$. Precise control of the cooling mechanism ensures that the grain boundaries are aligned vertically to the surface. Thus this starting material for solar cells is called polycrystalline silicon. This material is widely used and currently covers about 30% of all silicon requirements for terrestrial energy Photovoltaic. It is clear that parallel grain boundaries severely detract from the formation of a good p-n junction (leakage current, high saturation current).

1.4.2.3 Amorphous Silicon Solar Cells:

Amorphous materials differ from crystalline structures primarily because the strict periodicity of the lattice is not present. As a consequence, the normal selection rules for crystal do not apply. In particular, the absorption of light occurs directly. Amorphous silicon [a-Si] is a compound of silicon and hydrogen. The band gap of this semiconductor is approximately 1.7eV, but varies between certain limits due to the hydrogen content.

The current production method for a-Si solar cells involves depositing the individual layers in a high frequency glow discharge reactor. Silane (SiH_4) in a mixture with hydrogen is split into hydrogen and silicon. The a-Si can then be deposited onto glass or metal. The required p and n doping for the manufacture of solar cells are achieved by the addition of diborane (B_2H_6) or phosphine (PH_3). In the case of evaporation onto glass, the electrical contact is made using a conductive oxide film (TCO), Indium-Tin-Oxide (ITO) is often used for this purpose.

The diffusion length of the charge carriers was very strongly influenced by doping and was so extremely small that only a small part of charge carriers could be collected. A wide space charge region is created in which such high fields exist that almost all of the charge carriers created here can reach the p-n junction. As the absorption in this cell structure takes place almost exclusively in the intrinsic film, the efficiency could be raised to more than 5% for the first time. reach the p-n junction. As the absorption in this cell structure takes place almost exclusively in the intrinsic film, the efficiency could be raised to more than 5% for the first time.

Currently, solar cells made of amorphous silicon make up some 20% of current annual production (measured in peak watts). Their use in high performance applications is still strictly limited due to the importance of efficiency unless they are used more for architectonic reasons.

1.4.2.4 Other cells and materials:

Apart from silicon, some other thin film deposited materials, have the same advantages as the silicon thin film solar cells but their efficiency is better, can be used for manufacturing solar cells. The grid parity is achieved by the thin film technology. Gallium Arsenide (GaAs) is also a very interesting material for Photovoltaic. The energy gap of this semiconductor is 1.42 eV. It promises an almost optimal adaptation to solar radiation. The advantages of GaAs are:

- GaAs is also a direct semiconductor and therefore up to 90% of the sunlight is absorbed in a film thickness of 2 μm.
- The temperature dependency of efficiency in a GaAs is only one-third that of silicon due to the higher energy gap.

In addition, GaAs solar cells have a much lower sensitivity to cosmic radiation than the Si solar cells. The use of a GaAs substrate is a large cost disadvantage. One option is germanium, which has a thermal expansion mismatch of only 0.27% and therefore permits a relatively fault free precipitation of GaAs. Silicon would be very desirable as a substrate material for reasons of cost and better heat conductivity, but has an expansion mismatch of approximately 4%. Cadmium-Telluride is also a material that is used for photovoltaic. The energy gap of this semiconductor is 1.45 eV. CdTe is an almost optimal semiconductor like GaAs for the conversion of Sunlight. CdTe is a direct semiconductor and therefore sunlight is totally absorbed in a layer of a few μm thickness. Thus we studied different types of solar cells or materials whose voltage and current characteristics are non-linear and they are affected by irradiation and temperature.

The efficiency of different types of solar cells is shown in Table 1.2

Types of Solar cells	**Efficiency**
Mono-crystalline silicon solar cells	15-18%
Polycrystalline silicon solar cells	11-15%
Amorphous and thin-film silicon cells	6-8%

Table 1.2 Efficiencies of solar cells

1.5 PHOTOVOLTAIC ARRAY (PVA) POWER SYSTEM:

PV system is designed to give the electric supply to load and load can be ac type or dc type. Supply can be needed in day time or evening time or both time. PV system can give supply only in day time for night hours we needed supply for that we have batteries, where power can store and utilize. Solar PV system can be classified into stand-alone systems (off-grid) and grid connected (grid-tied) systems.

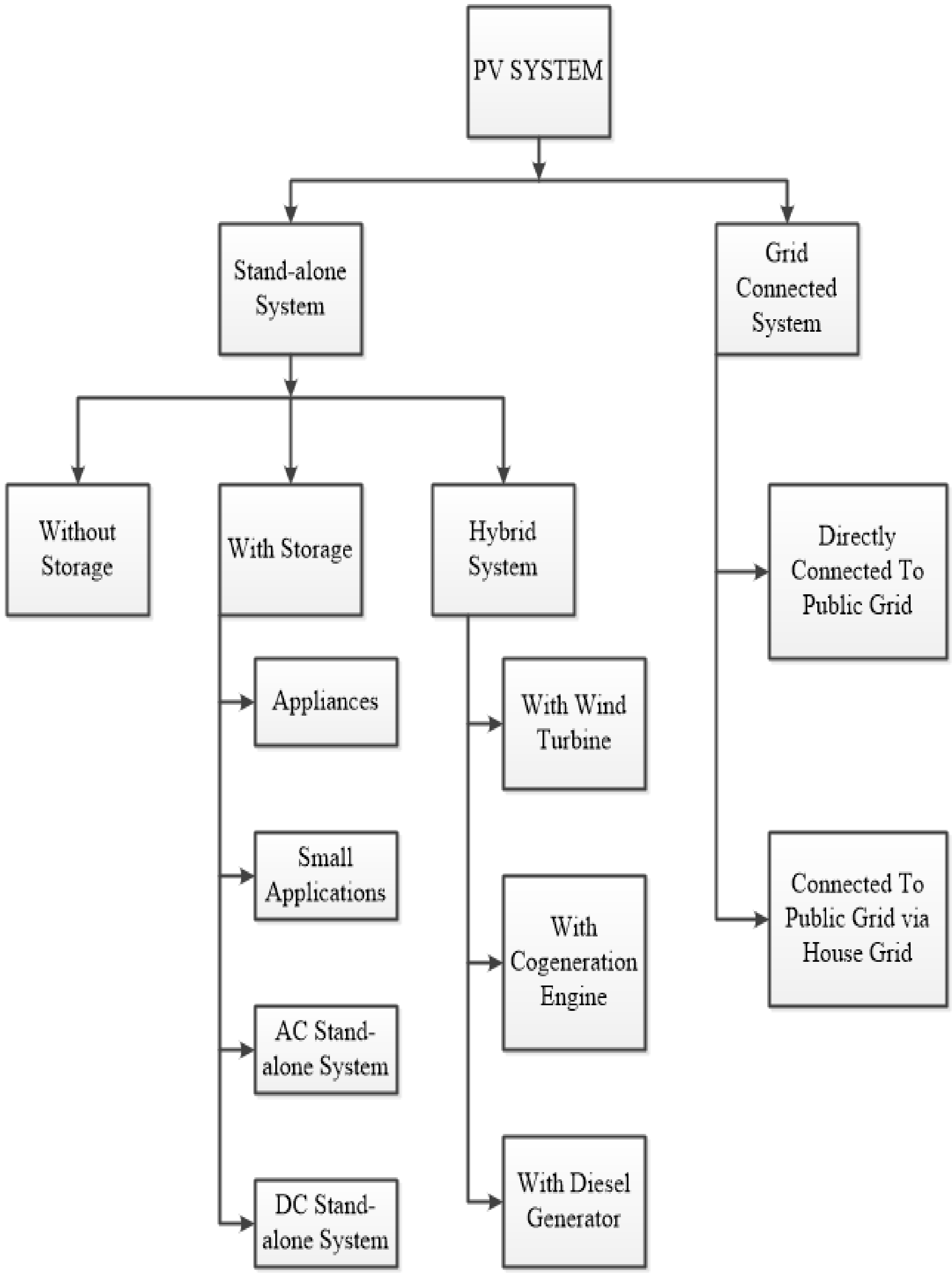

Figure 1.4: Different types of interconnection of solar Photovoltaic (SPV) power generating system to grid

1.5.1 Stand-Alone System:

This mode of energy generation from solar energy consists of systems which are not connected to the grid, i.e. off-grid applications. It is done especially in the places where there is acute scarcity of electricity derived from conventional sources. These stand-alone systems have a solar array coupled with a power conditioning device such as an inverter that converts the power from DC to AC to suit the load requirements, such as home power, and a battery to store the solar energy harnessed during the day which is to be consumed in the absence of solar energy. These decentralized systems of PV arrays operate at parameters below 33KV and 50Hz through the inverter. The heating systems concentrate the solar rays on heating water which can be used for cooking, washing, power generation, etc.

Depending on the type of load, cost, resources availability and requirements of the load stand-alone system divided into several categories, which are describe below:

- Unregulated standalone system with DC load
- Regulated standalone system with DC load
- Regulated standalone system with battery and DC load
- Regulated standalone system with battery, AC and DC loads

1.5.1.1 Unregulated Standalone System With DC Load:

Usually this type of system is for low power applications. A PV system is directly connected to the load without any MPPT controller, night hours it will not provide any supply because of the absence of the battery.

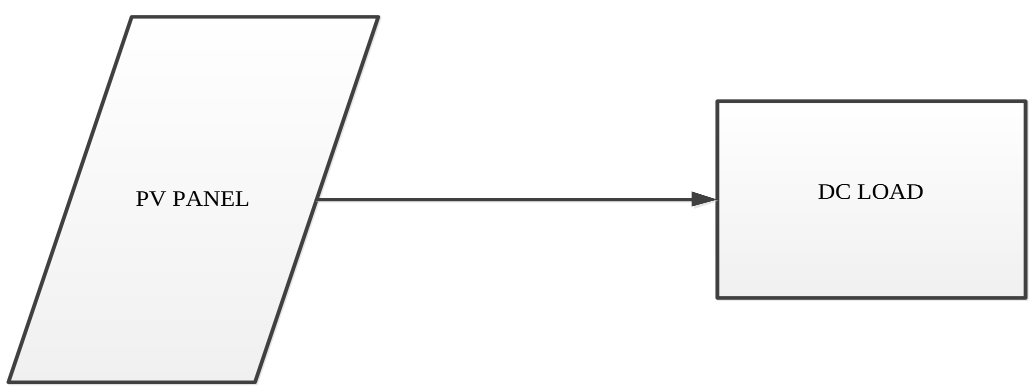

Figure 1.5: Unregulated standalone system with DC load

1.5.1.2 Regulated Standalone System With DC Load:

It is similar to unregulated standalone system with DC load but basic difference between this and previous one that this system requires a MPPT technique. Usually system with MPPT should have one battery otherwise extra power will be waste.

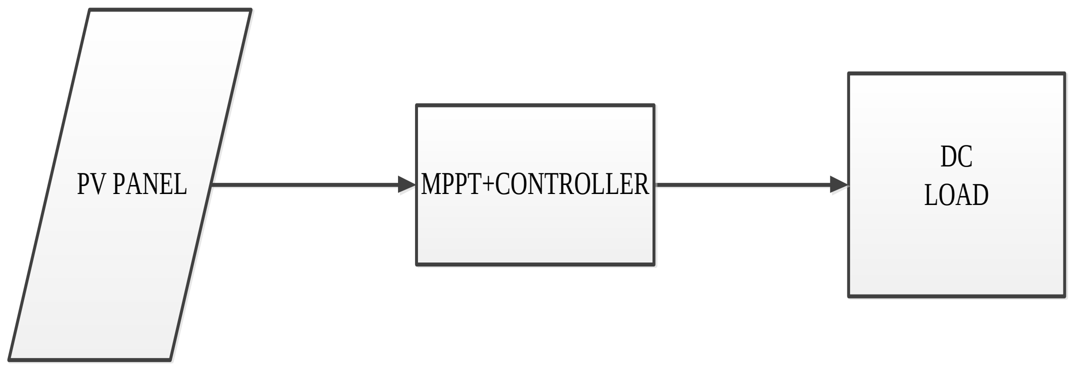

Figure 1.6: Regulated standalone system with DC load

1.5.1.3 Regulated Standalone System With Battery And DC Load:

Most common configuration PV array, battery, MPPT and DC load. Battery use to store the extra power of PV system, this will increase the cost of PV system. A charge controller is must for this type of system because battery life is less compare to PV module, extra charging deep discharging can reduce the life of battery.

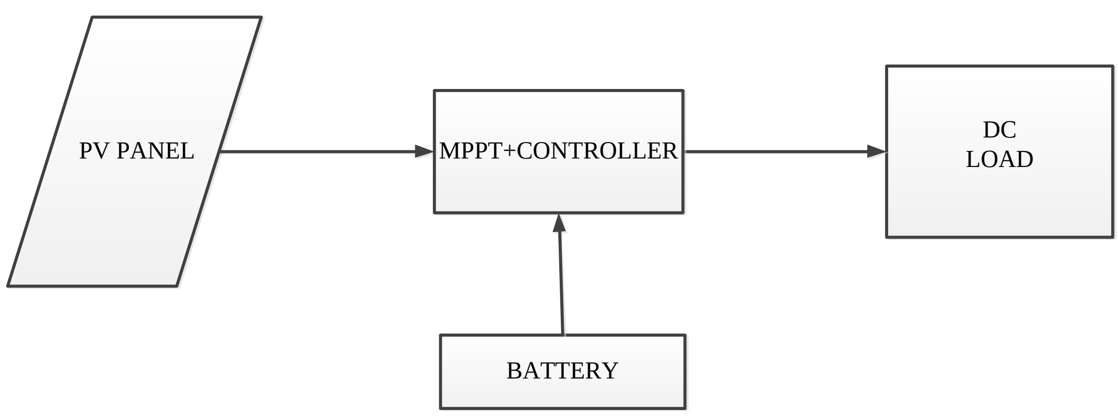

Figure 1.7: Regulated standalone system with battery and DC load

1.5.1.4 Regulated Standalone System With Battery, AC And DC Loads:

This system is similar to previous one but here AC load can also draw the power from PV system and inverter (DC to AC converter) is require, it will increase the cost.

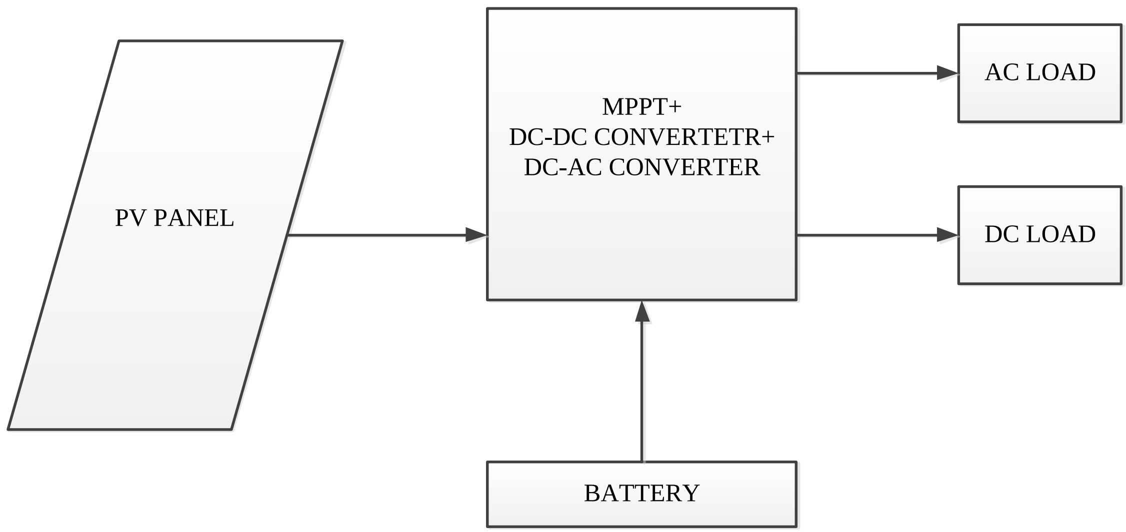

Figure 1.8: Regulated standalone system with battery, AC and DC loads

1.5.2 Grid-Connected System:

Grid connected PV system is a system when grid is connected to PV system. In this mode of solar power generation, the solar arrays are used in large capacities of the order of MW for the generation of bulk power at the solar farms, which are coupled through an inverter to the grid and feed in power that synchronizes with the conventional power in the grid. The grid connected solar power operates at 33KV and at 50 Hz frequency through inverter systems, whereas the solar farms generate the average power output of about 5MW each. Grid connected system deals with very high power applications. Owing to quite high power generations, the batteries are not used to store power as in the case of isolated power generation for economic concerns.

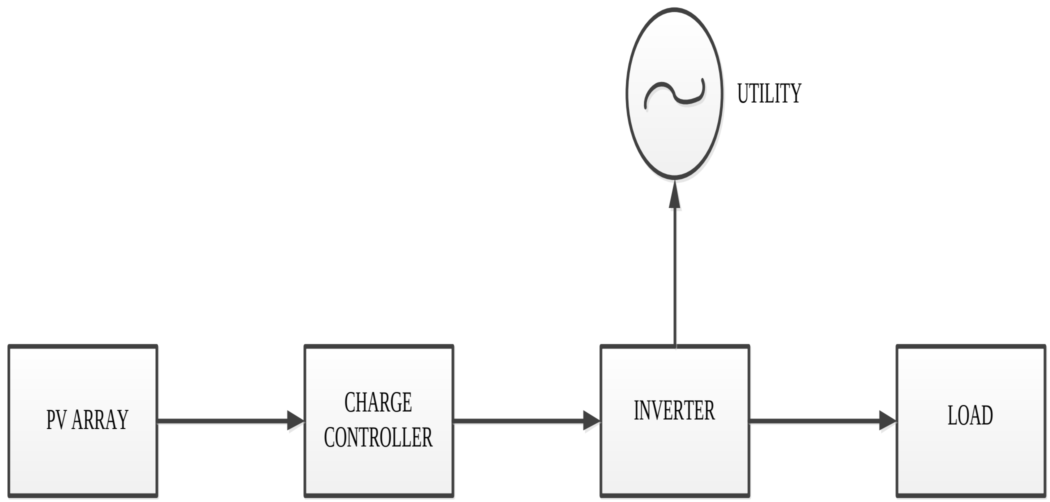

Figure 1.9: Grid interactive PV system

1.5.3 Hybrid system:

When PV system is used in conjunction with diesel generator, wind generator, micro turbines, fuel cells etc. then the system is called Hybrid system.

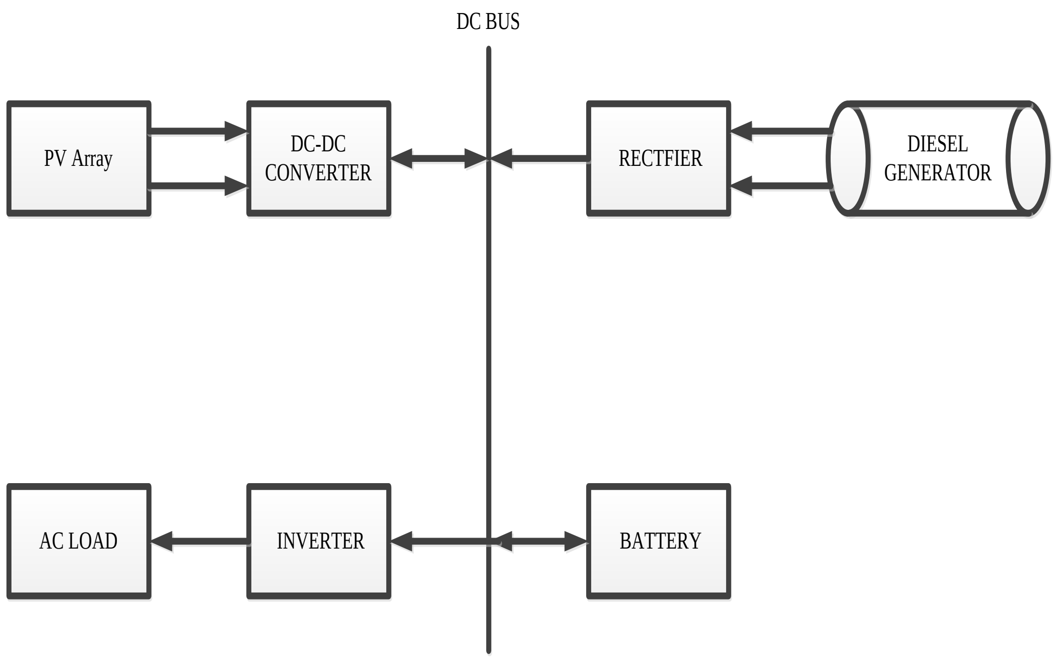

Figure 1.10: Hybrid system

1.6 ORGANIZATION OF THESIS:

The chapter wise description of this dissertation is given as under:

Chapter -1 gives a brief introduction of different type of solar cell materials and ways to improve the efficiency of the solar PV system. The PV array system can be used in different modes like stand-alone mode and grid connected mode.

Chapter-2 presents a brief literature review of Solar cell, MPPT and Grid connected Solar PV system.

Chapter-3 presents different electrical equivalent models of solar cell and the design of modules, string and array is studied.

Chapter 4 presents different MPPT algorithms in which Perturbation and observation algorithm of MPPT has been modelled and simulated successfully in MATLAB/Simulink environment. The maximum power point (MPP) for PV array voltage and current is achieved and so that maximum power is obtained. Boost converter is designed successfully along with MPPT algorithm.

Chapter 5 presents the grid connected SPV power generating system whose performance is investigated and analyzed successfully. The models are simulated for linear and non-linear load. Results for grid power quality improvement have been obtained successfully.

Chapter 6 gives the main conclusion and future scope of the work.

CHAPTER 2
LITERATURE REVIEW

2.1 Literature Review:

Subarto Kumar Ghosh et. al presented a simulation model to study and analyze the performance of a PV array with changing atmospherically parameters like temperature and irradiance etc. The I-V characteristics of proposed PV model are simulated in MATLAB/ Simulink. This proposed electrical model of PV array is presented based on the Shockley diode equation. A 550W solar array was used for Standalone system analyzed [1].

R.Chedid et. al presented a teaching approach for modeling and simulating the PV cells in order to consider the effects of temperature, irradiance, series and parallel connections of modules and shading. Using basic electric circuit laws the Equations are derived and MATLAB code is provided to aid students and engineers better understand PV operational characteristics through simulation [2].

Tom Markvart et.al describes a Photovoltaic energy conversion consisting of two necessary steps. An electron hole pair is generated by absorption of light. The device separates electron-hole pair that electrons to the negative terminal and holes to the positive terminal, generate electrical power. The proposed system shows the principal features of the typical solar cells. Device's physical structure and the dominant electron transport processes are presented to contribute to the energy-conversion process [3].

Huiying Zheng et.al developed a system in MATLAB/Sim Power Systems and real-time simulation system for fast and accurate performance evaluations of PV arrays under high frequency switching operations of power electronics converters. Different MPPT control techniques are investigated for solar PV system. The proposed system shows the effect of sampling rate and time delay on PV system performance with different MPPT control techniques. The proposed system also deals with the behavior of MPPT techniques under fast changing weather conditions [4].

Trishan Esram et. al presented the techniques for maximum power point tracking of solar PV arrays. The techniques are taken from the literature dating back to the earliest methods. Several methods have been introduced and implemented with many variations. The proposed system also served as a convenient reference for future work in Photovoltaic power generation [5].

Moein Jazayeri et. al focussed performance evaluation of “Perturb & Observe” and “Incremental Conductance” algorithms to track the Maximum Power Point for photovoltaic systems. The Proposed model simulated in MATLAB/SIMULINK platform. The simulation model of a PV module is constructed based on the one-diode mathematical model of a solar cell. A boost type DC/DC converter topology is modeled and simulated for “P&O” and “Inc & Cond” algorithms. The proposed system provides the performance and characteristics of the MPPT techniques to improve the overall efficiency and reduce the cost of PV system applications [6].

D. S. Karanjkar et. al presented the maximum power point tracking (MPPT) system that controls the voltage and the current output of the PV system to deliver maximum power to the load. The proposed system deals with real time simulation and comparative analysis of perturb and observe, incremental conductance. Performance of MPPT methods have been compared based on tracking efficiency, steady state and dynamic behaviour. Experimental results of various MPPT techniques have been presented for tracking maximum power point under rapidly varying solar radiations [7].

Dr. Tilak Thakur et. al presented a control algorithm to control the active and reactive power flow. There are two methods namely two stage or single stage method that PV system can be connected to the grid. This system uses a single stage method to reduce the cost and losses of the system. Control scheme is implemented to provide maximum active power and reactive power according to the load or grid requirement. Photovoltaic module simulation is done by using the data based MPPT technique. [8].

Ahmed S. Khalifa et. al presented a control method to integrate medium and large PV generation system to the distribution grid. The proposed system consists of a PV system with a power electronic interface to the grid integration. The power electronic interface system consists of a DC-DC boost converter and a current controlled Voltage Source Inverter (VSI).The main objective of the controller is to inject a pure sinusoidal current into the grid. Modeling PV cell and maximum power point tracking (MPPT) algorithms has been also described in detail. The results of the proposed system are simulated using MATLAB/SIMULINK. A case study is carried out to observe the effect of the interfacing transformer topology on the system during faulty conditions [9].

Atiqah Hamizah et. al proposed a mathematical modeling and circuit-based approach for designing PV arrays with MPPT controller. To draw the PV and IV characteristics of the PV array, the input parameters are temperature and irradiance. The P&O approach is implemented for tracking the maximum power point (MPP) along the PV curve [10].

M.Makhlouf et. al described about traditional energy resources in which PV system use solar energy to produce electricity. The disadvantage of PV generation is that it depends on weather conditions. The system developed some control techniques for three phase grid connected PV systems and DC link voltage control can be stabilized the voltage at the inverter input. The proposed system presented a modeling of the grid-connected PV system components that is simulated in MATLAB/Simulink [11].

Bhim Singh et. al proposed a grid connected solar photovoltaic (SPV) power generating system consisting of a SPV, DC/DC boost converter, voltage source converter (VSC), interfacing inductors, ripple filter and a three phase grid feeding variety of linear and nonlinear loads. The reference grid currents are estimated by using power balance theory (PBT) to control the three-leg voltage source converter (VSC). This proposed SPV power generating system for unity power factor, reactive power compensation for voltage regulation in a three phase distribution system. The DC link voltage of VSC is regulated through a DC voltage PI controller and the MPPT is achieved using a DC/DC boost converter. The grid interfaced SPV power generating system is modeled and simulated in the MATLAB/Simulink [12].

Sidharth Rajamohan et. al focussed the design of a grid connected PV system. The I-V and the P-V characteristics of a PV array are observed to determine the MPP. The design of a dc-dc boost converter used as a voltage controller in the PV system. An effective control scheme for injecting the current into the grid is implemented. A conventional technique based on dual Hysteresis-band current control for variable load conditions is simulated and the results studied. This conventional control technique is suggested to be replaced with a current control scheme in the stationary (α;β) reference frame. This method is based on space vector modulation and hysteresis-band current control where the three hysteresis band form a hysteresis hexagon [13].

Rajan Kumar et. al proposed a study of power quality (PQ) improvement in a 3-Φ grid connected photovoltaic (PV) system. The variable step perturb & observe maximum power point tracking (MPPT) scheme has been implemented to force the PV generation to reach the maximum power operation. A battery energy storage system (BESS) via a bi-directional DC/DC converter is introduced in the DC bus to maintain the DC bus voltage level at a constant value. A 3-Φ hybrid filter is connected into the utility grid for reactive power compensation and the load current harmonics, generated by the non linear load. The performance study is simulated under variations of sola insolation and loads [14].

Fei Liu et.al theoretically described mathematical modeling of a three phase, single stage PV converter with LCL filter. Authors proposed a pole assignment control method that is based on feedback and repetitive controller of current regulation. A MPPT technique is implemented using improved P&O method with adaptive step technique, a constant voltage tracking method can also be implemented in the MPPT controller. The rate of change of the DC bus voltage decides the control measures taken by the adaptive step algorithm. Finally the authors presented the simulated results with the experimental validations [15].

Lakshmanan.S.A et.al presented different Pulse Width Modulation (PWM) techniques that have been implemented for grid connected 3-phase Voltage Source Inverter (VSI) system. Authors proposed few types of PWM techniques and mathematical model of LC filter circuit using state space analysis. Sine-PWM technique is proposed for 3-phase VSI and implemented using the state space model of the LC filter circuit. The simulation is performed in MATLAB/Simulink platform. Simulation results are presented for the inverter and load side to demonstrate the satisfactory performance of the sine-PWM technique [16].

K K Prajapat et.al presented solar PV Panels, one inverter, one charge controller and a battery bank. The load requirement is fulfilled by the PV system. One varies up to 3% over a year and the second one shows a much greater variability. The output power of photovoltaic (PV) module varies with module temperature, solar isolation, 1oad changes etc. The output power of single-phase grid-connected PV system is controlled according to the output power of PV arrays. The proposed system is simulated in MATLAB/SIMULINK and results show that the proposed method has a good performance [17].

Nidhi Agarwal theoretically described the conversion of solar energy to electrical one. Two different methods are used to maximize the generated power. A comparison between the 'perturb and observe' and the 'incremental conductance' control method are analyzed and discussed for solar panel. The solar panel is modelled and analyzed in MATLAB/SIMULINK. The implemented model of the photovoltaic (PV) array is started together with the buck converter and MPPT control have been simulated the PV systems with both MPPT algorithms at different solar radiation and temperature. The general topologies, sizing criteria, and control are presented as well as on efficiency and also the simulations result show the effectiveness to produce a more stable power [18].

Ahmed M. Atallah et. al described MPPT technique used to extract maximum energy from the Photovoltaic (PV) Systems. Low energy conversion efficiency and high initial cost are the two major barriers used in PV system. Authors presented implementation of Perturb and Observe MPPT using buck and buck-boost Converters. The current, voltage and output power for each various combination have been recorded. The simulation has been implemented in software of MATLAB/SIMULINK [19].

Kun Ding et. al proposed the performance of a photovoltaic (PV) module is mostly affected by array configuration, irradiance, and module temperature. The proposed PV module model is simulated in MATLAB/SIMULINK that includes a controlled current source. Under non-uniform irradiance, the model is practically validated by using different array configurations in testing platform. The proposed model can also simulate electric circuit and its maximum power point tracking (MPPT) in MATLAB-Simulink [20].

CHAPTER 3

SOLAR PHOTOVOLTAIC ARRAY (SPVA)

3.1 GENERAL:

Photovoltaic (PV) are solid-state, semi-conductor type devices that produce electricity when exposed to light. The word ‘Photovoltaic’ actually mean "electricity from light". Solar PV is modeled using electrical equivalent circuit of solar cell and the related mathematical equation for equivalent models is presented. In this chapter different types of equivalent models have been discussed and the characteristics of PV array are shown. The effect of parameter variation on PV characteristics is obtained and discussed along with the design of module and array is shown.

3.2 EQUIVALENT CIRCUIT OF SOLAR CELL AND EQUATIONS:

There are many types of electrical equivalent models for solar cell modelling and each model will yield different types of mathematical equation due to different number of components in the circuit of solar cell. Four types of the different PV cell models are shown:

3.2.1 Double diode model (Double exponential model):

This model is called as double diode model and also termed as generalized model because it is most ideal model to give approximately ideal characteristics. It consists of two diodes D1 and D2 and two resistances i.e. series resistance (Rse) and parallel resistance (Rsh) and equation (2.1) shows the output current of solar cell.

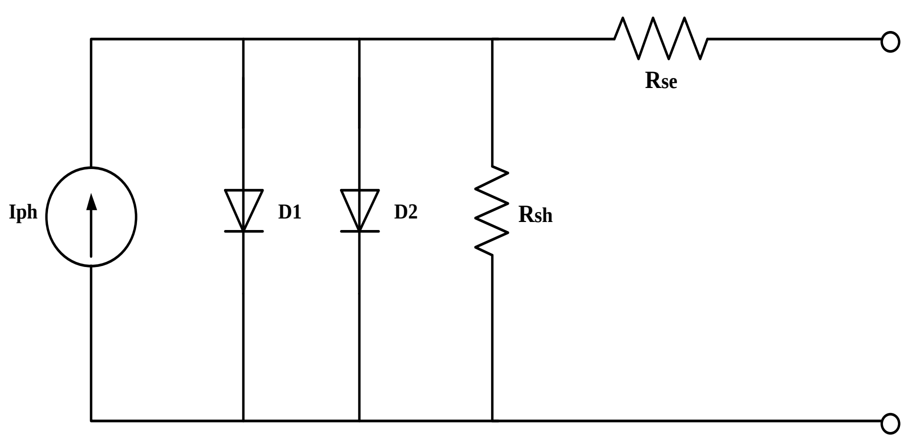

Figure 3.1: Double diode model of Solar cell

$$I = I_{ph} - I_{s1}\left(e^{V+IR_{se}/NV_t}\right) - I_{s2}\left(e^{V+IR_{se}/NV_t}\right) - \frac{V + IR_{se}}{R_{sh}} \tag{3.1}$$

3.2.2 Single diode model (General Model):

It is called as single diode model and also known as general model because it is the commonly used model for the purpose of research. It consists of single diode but consists of both resistances i.e. series resistance (Rse) and parallel resistance (Rsh) and equation (2.2) shows the output current of solar cell.

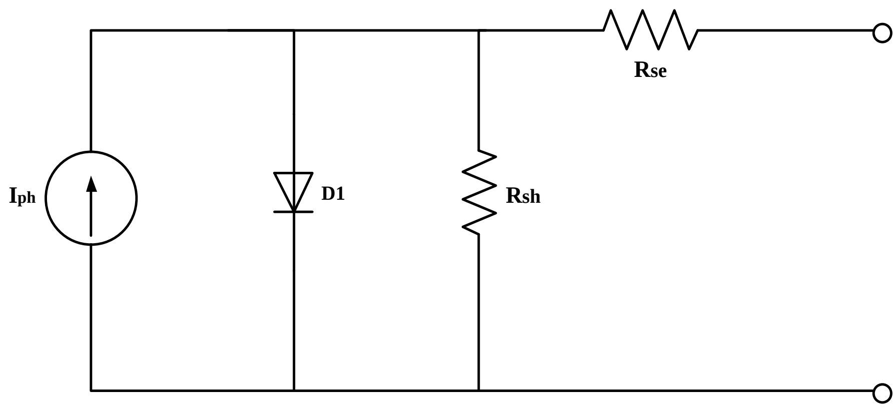

Figure 3.2: Single diode model of Solar Cell

$$I = I_{ph} - I_s\left(e^{V+IR_{se}/NV_t}\right) - \frac{V + IR_{se}}{R_{sh}} \tag{3.2}$$

3.2.3 Appropriate model:

This one is the appropriate model of photovoltaic model consisting of only one diode D and one series resistance (R_{se}) and equation (2.3) shows the output current of solar cell.

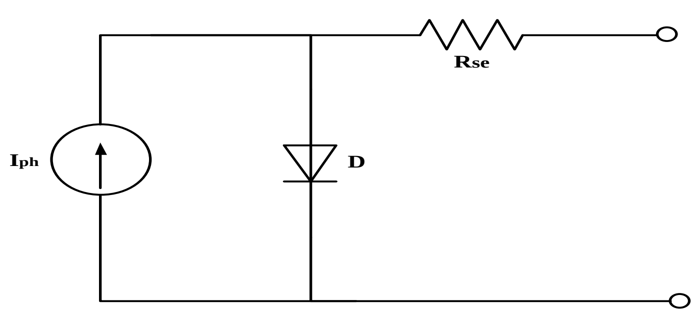

Figure 3.3: Appropriate model of Solar cell

$$I = I_{ph} - I_s\left(e^{V+IR_{se}/NV_t}\right) \tag{3.3}$$

3.2.4 Simplified model:

The most simplified model of solar cell is shown with a current source and a diode in parallel and equation (2.4) shows the output current of solar cell where I and V are the solar cell output current and voltage respectively, (I_{ph}) is the light generated current, I_{s1} and I_{s2} are the dark saturation current, q is the charge of an electron, N is the diode quality (ideality) factor, Vt is thermal voltage and given by Vt=kT/q; k is the Boltzmann constant, T is the absolute temperature and (R_{se}) and (R_{sh}) are the series and shunt resistances of the solar cell.

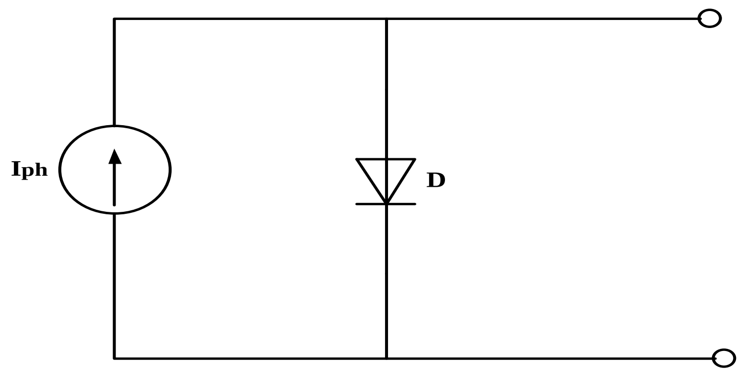

Figure 3.4: SPV from Cell to Module

$$I = I_{ph} - I_s\left(e^{V/NV_t}\right) \tag{3.4}$$

3.3 SOLAR CELL, MODULE AND ARRAY:

A single individual solar cell can produce only about 0.5-0.7V and this is a rare application for a single cell is of any use. Photovoltaic cells combine to form photovoltaic systems. A module is a basic building block for PV applications which consists of a number of pre-wired cells in series encased in tough weather resistant packages. Different types of PV systems starting from a cell up to array.

3.3.1 From cells to module:

When we wired the photovoltaic cells in series then each cell carry the same current and at any given current their voltages add. To increase the voltage, we wired several modules in series and to increase the current, wired several modules in parallel. Thus the product of both voltage and current is power. To find that how many modules should be connected in series and how many connected in parallel to deliver whatever energy is needed, an important element in PV system is designed.

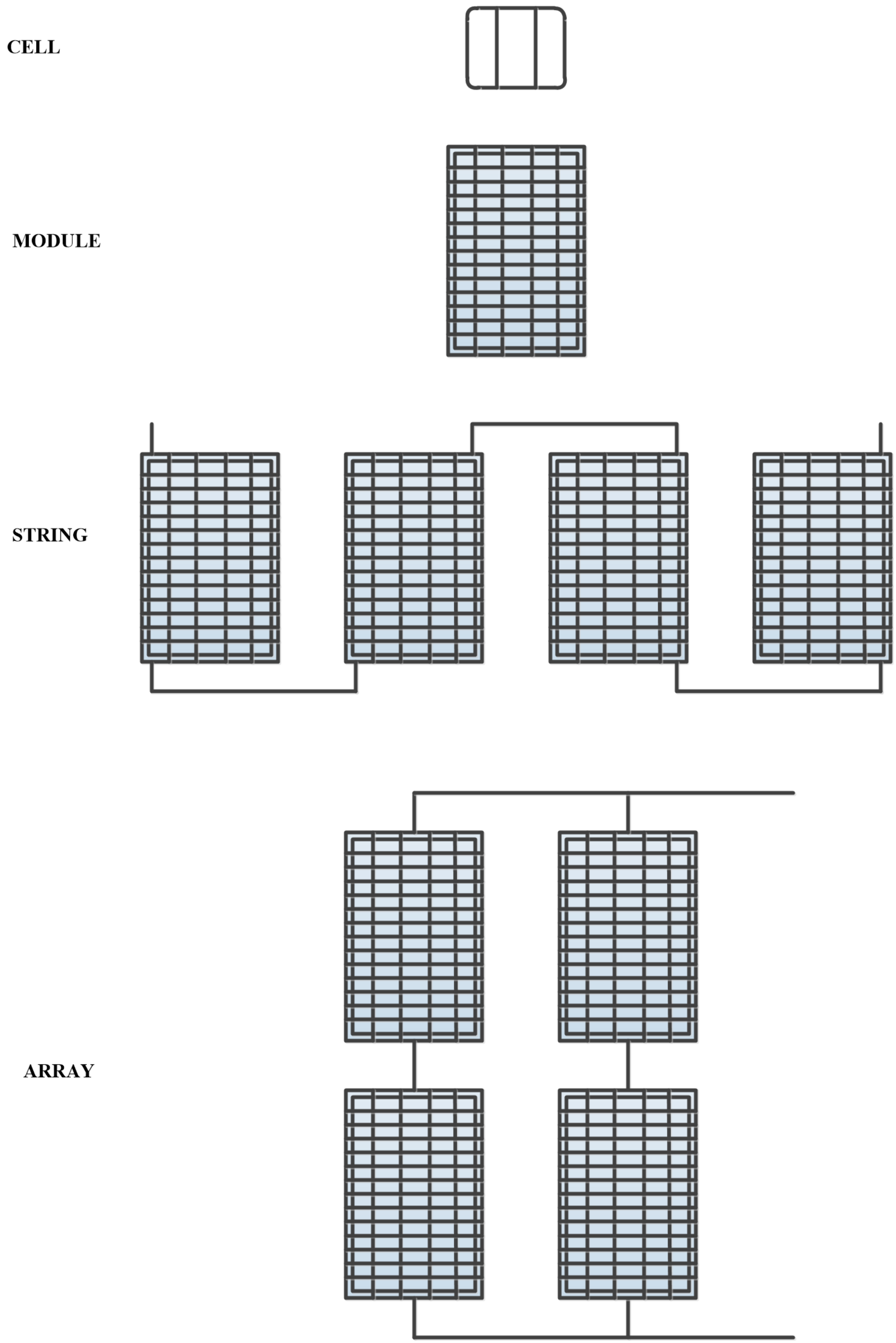

Figure: 3.5 SPV from cell to array

3.3.2 From Module to Array:

To increase the Voltage and current, we wired module in series and in parallel respectively. Power can be increased by the combination of series and parallel modules. This combination of some series and parallel modules are known as Arrays. When modules are in series then the I-V curves are simply added along the voltage axis. When modules are in parallel then each module has the same voltage and the total current is the sum of the currents. When high power is required, then we combine the series and parallel modules for which the total I-V curve is the sum of the individual module I-V curves.

For a certain PV panel, the voltage-power characteristics are fixed for different irradiance without intersection. Hence, if the value of voltage and power is given then the value of required irradiance can be estimated. PV output current varies with irradiance and the operating point changes with the solar irradiance, temperature and load conditions. With the increase in operating temperature the output current increases but the value of voltage decreases drastically. This results in the reduction of the output power. To increase the output voltage PV modules can be connected in series to form an array.

CHAPTER 4

MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES AND DESIGN OF BOOST CONVERTER

4.1 GENERAL:

The role of Maximum Power Point in photovoltaic system is very important because the power output from a PV system is maximized by the MPP. Only 30 to 40 percent of the incident solar irradiation is converted into electrical energy by solar panel. The efficiency of the solar panel is improved by the MPPT technique. The voltage at which maximum power is produced by PV module is called 'maximum power point' (or peak power voltage).

To track maximum power point, technique use called maximum power point tracking technique. To obtain the maximum amount of energy, the PV system track the solar panel at the maximum power point that varies with the irradiance and temperature. The primary challenges for maximum power point tracking of a solar PV array include:

- how to get to a MPP quickly
- how to stabilize at a MPP and
- how to smoothly transition from one MPP to another for sharply changing weather conditions.

In general, we can say that temperature is inversely proportional and irradiation is directly proportional to output power. A fast and reliable MPPT is critical for power generation from a solar PV system. In this Chapter different MPPT methods are discussed and design of boost converter is also shown.

4.2 DIFFERENT MPPT TECHNIQUES:

The efficiency of the solar panel is increased by the Maximum Power Point Tracking algorithm because as the irradiation and temperature varies, the MPP of a solar panel also varies, so maximum power is obtained from a solar array with the use of MPPT algorithms. Different MPPT techniques are used to track the maximum power that is generated by the PV array in different environmental condition. MPPT techniques vary according to their different working algorithm, parameters and equations which are used. Several MPPT methods have been studied and researched. The following are the few MPPT techniques which have been introduced here. Among all these techniques the most commonly used technique is Hill Climbing/Perturbation and Observation (P & O).

4.2.1 Perturb & Observe/ Hill Climbing Method:

Perturb & Observe method is the most frequently used algorithm to track the maximum power due to its simple structure and fewer required parameters. P&O is similar to the hill climbing method only one difference is that hill climbing method deals with perturbation in duty cycle and P&O method deals with perturbation in voltage. This method finds the maximum power point of PV modules by means of iteratively perturbing, observing and comparing the power generated by the PV modules. It is widely applied to the maximum power point tracker of the photovoltaic system for its features of simplicity and convenience.

The required parameters of the power-feedback type MPPT algorithms are only the voltage and current of PV modules that is the relationship between the terminal voltage and output power generated by a PV module. It can be observed that regardless of the magnitude of sun irradiance and terminal voltage of PV modules, the maximum power point is obtained while the condition $dP/dV = 0$ is accomplished.

The flow chart of this algorithm is given below in figure 4.1:

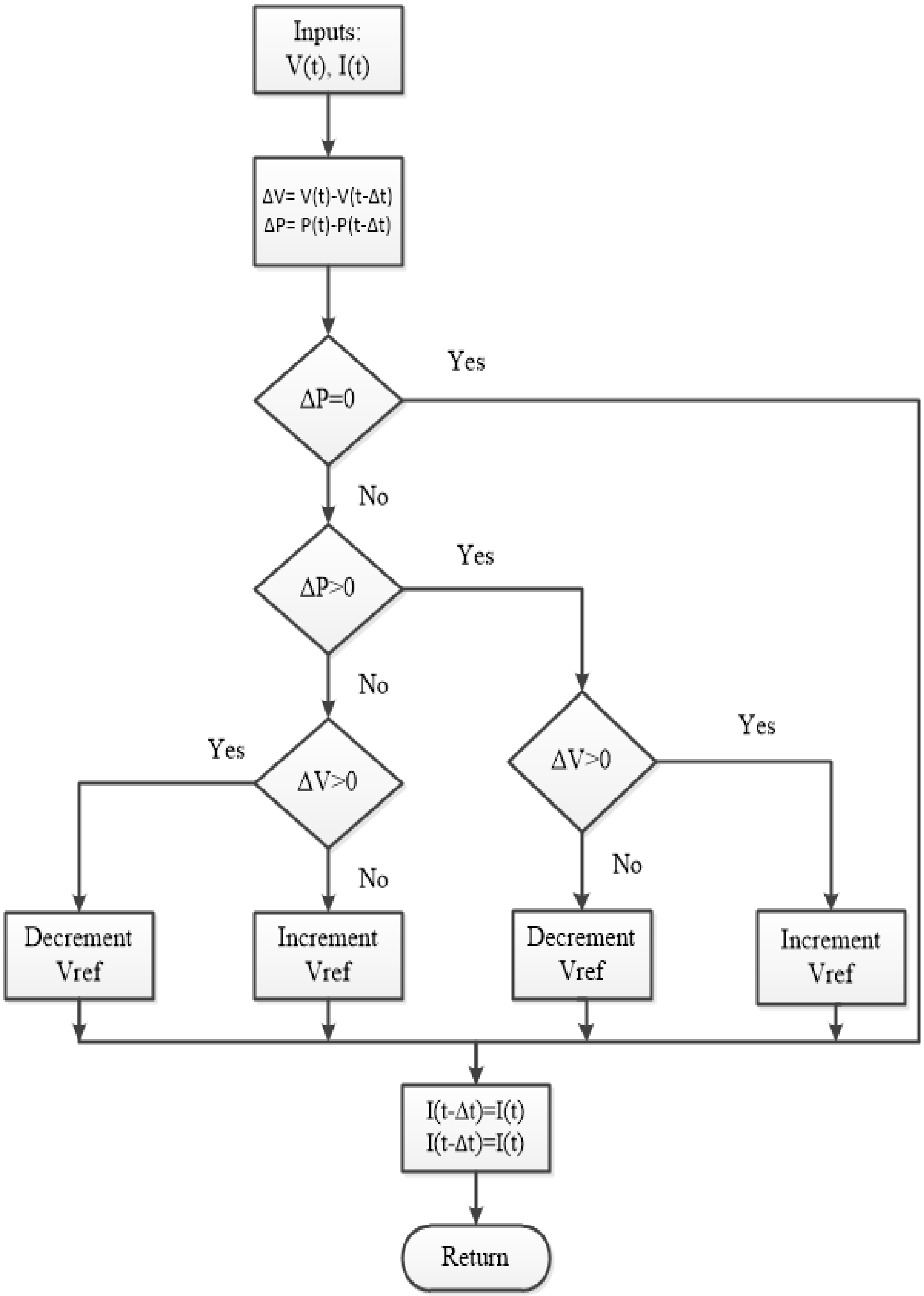

Figure 4.1: Flow chart for Perturb and observe algorithm

The basic operating procedure of P&O method is shown in Fig. 4.1 In a fixed period of time, the load of the PV system is adjusted in order to change the terminal voltage and output power of the PV modules. The variations of the output voltage and power before and after changes are then observed and compared to be the reference for increasing or decreasing the load in the next step. If the perturbation in this time results in greater output power of PV modules than that before the variation, the output voltage of PV modules will be varied toward the same direction. Otherwise, if the output power of PV modules is less than that before variation, it indicates that the varying direction in the next step should be changed. The maximum output power point of a PV system can be obtained by using these iterative perturbation, observation and comparison steps.

The advantages of the P&O method are simple structure, easy implementation and less required parameters. The shortcomings of the P&O method can be summarized: (a) The power tracked by the P&O method will oscillate and perturb up and down near the maximum power point. The magnitude of oscillations is determined by the magnitude of variations of the output voltage. (b) There is a misjudgment phenomenon for the P&O method when weather conditions change rapidly.

Benefits:

1) This algorithm is very simple.
2) Its implementation is easy.
3) Low cost.
4) It is a comparatively an accurate method.

Drawbacks:

1) It is very difficult to determine when it has actually reached the MPP. Under steady state operation the output power oscillates around the MPP.

For our project we choose Perturb and observe algorithm as it has more advantages over drawbacks. The oscillation problem can easily be minimized using minimization techniques by controller.

4.2.2 Incremental Conductance Method:

When the operating behavior of PV modules is within the constant current area, the output power is proportional to the terminal voltage. That means the output power increases linearly with the increasing terminal voltage of PV modules (slope of the power curve is positive, dP/dV > 0). When the operating point of PV modules passes through the maximum power point, its operating behavior is similar to constant voltage. Therefore, the output power decreases linearly with the increasing terminal voltage of PV modules (slope of the power curve is negative, dP/dV < 0). When the operating point of PV modules is exactly on the maximum power point, the slope of the power curve is zero (dP/dV = 0) and can be further expressed as,

- dP/dV = 0 at MPP
- dP/dV > 0 left of MPP
- dP/dV < 0 right of MPP

But

$$\frac{dP}{dV} = I + V\frac{dI}{dV} \approx I + V\frac{\Delta I}{\Delta V} \tag{4.1}$$

Here dI and dV represent the current error and voltage error before and after the increment respectively. Therefore we will get the new condition by differentiating power with respect to voltage given as

$$\begin{aligned} \Delta I/\Delta V &= -I/V && \text{at MPP} \\ \Delta I/\Delta V &> -I/V && \text{left of MPP} \\ \Delta I/\Delta V &< -I/V && \text{right of MPP} \end{aligned} \tag{4.2}$$

The flow chart of this algorithm is given below:

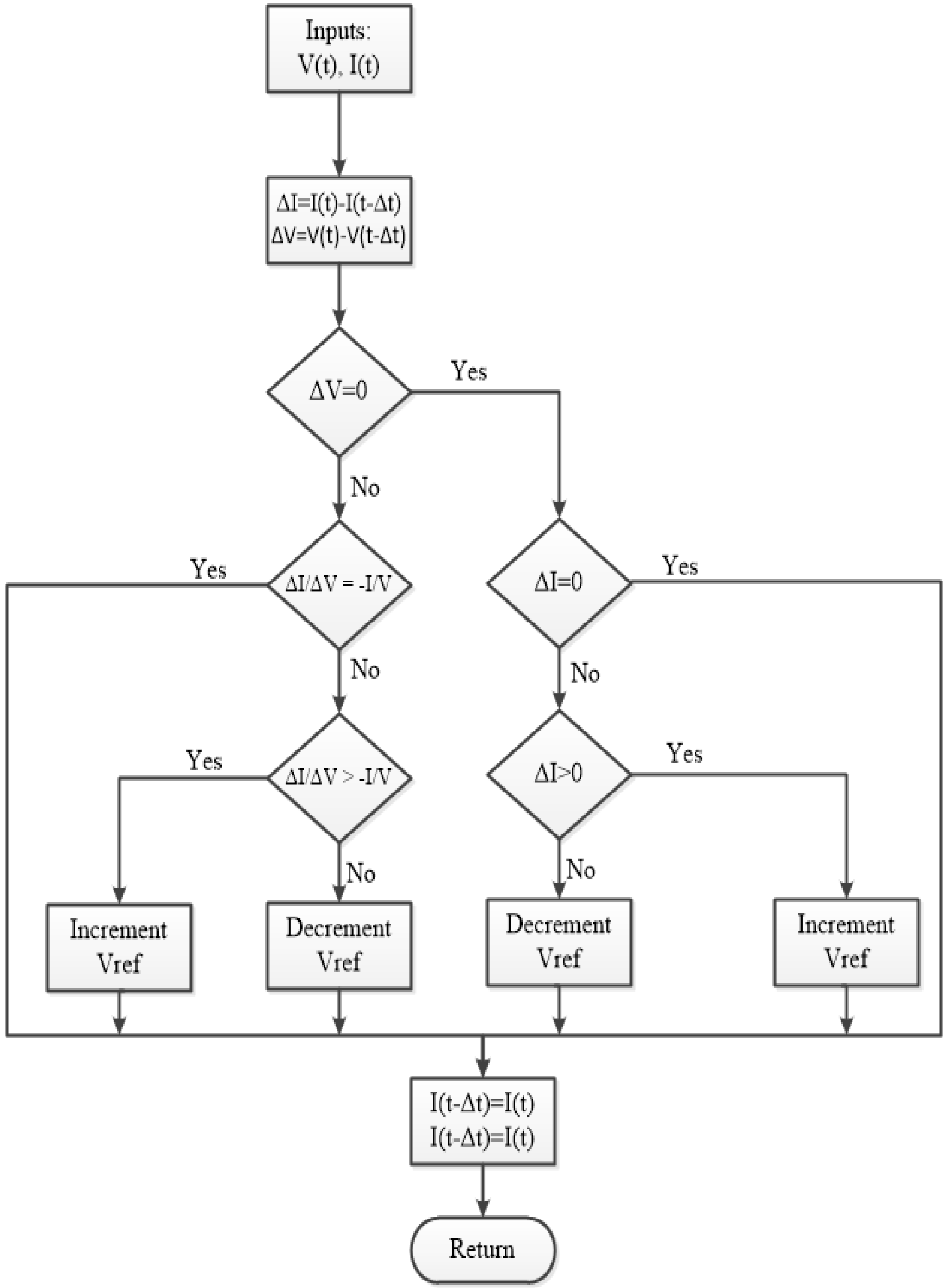

Figure 4.2: Flow chart for incremental conductance algorithm

Hence MPP can be tracked by comparison of incremental conductance and instantaneous conductance. The main difference between incremental conductance and P&O algorithms is the judgment on determining the direction of voltage perturbation. The advantage of the incremental conductance method, which is superior to those of the other two MPPT algorithms, is that it can calculate and find the exact perturbation direction for the operating voltage of PV modules. In both P & O and incremental conductance methods, the speed of response of MPP depends upon the size of the increment of the reference voltage. The drawback of both the methods is that it is unable to track maximum power point (MPP) if there are rapid changes in parameters i.e. irradiance and temperature. The other drawback of both the methods is that the oscillation occurs at the point of MPP which results in oscillations in voltage and current at MPP level.

4.2.3 Fractional Open circuit Voltage:

This is also called as fractional open-circuit voltage method. MPP voltages is fractional of open-circuit voltage of PV system, that can be described as following equation,

$$V_{MPP} \approx k_1 V_{oc} \tag{4.3}$$

Where k_1 is between 0.71 to 0.78

Under different irradiance condition, this coefficient k_1 will not change much. The MPP voltage decreases slightly when sunlight is reducing. Similarly the open-circuit voltage also decreases accordingly, the ratio between MPP voltage and open-circuit voltage on each curve is kept at k1. V_{MPP} and V_{oc} for a specific PV array is computed beforehand empirically at different temperatures and insolation levels. When the k_1 is known for specific PV array it needs to open circuit the PV array periodically to measure V_{oc} hence there is power loss occurs. The PV array operates at MPP (approximately).This method has low power generation efficiency. Advantage of this method it is easy to implement and it is cheap.

Benefits:

1. Relatively lower cost
2. Very simple and easy to implement

Drawbacks:

1. Not accurate and may not operate exactly at MPP
2. Slower response as V_{MPP} is proportional to V_{oc}.

4.2.4 Fractional Short circuit Current:

This method is similar to fractional open circuit voltage method. Current I_{MPP} is proportional to I_{sc}.

$$I_{MPP} \approx k_2 I_{SC} \tag{4.4}$$

Where $k_2 \cong$ 78% to 92 % measuring Isc during operation is though need one extra switch. It will increase the cost and calculated value is also not so accurate.

Benefits:

1) It is simple and low cost to implement.
2) This method does not require an input.
3) In low insulation conditions, it is better than others.

Drawbacks:

1) Irradiation is never exactly at the MPP due to variations on the array that are not considered (it is not always accurate).
2) Data varies under different weather conditions and locations.
3) It has low efficiency.

4.3 DESIGN OF DC-DC BOOST CONVERTER:

The Perturb and Observe method is used to track the maximum power point for current and voltage. By using MPPT and DC-DC boost converter, the voltage at the load terminal of PV array system is boosted according to the change in load. The voltage and current is modulated at the load side but the power remains constant at a particular level even with the change in load. According to the desired output levels, the value of inductor and capacitor is designed and calculated. The design of Boost converter is shown below:

$$L = \frac{V_{pv} D}{2 \Delta i_1 f_{sh}} \tag{3.5}$$

$$C = \frac{I_d D}{\Delta V f_{sh}} \tag{3.6}$$

Where

V_{pv} = PV side Output voltage

D = Converter’s duty cycle

Δi_1 = Input current (PV side) ripple

I_d = Load side Output current

ΔV = Output voltage (load side) ripple

f_{sh} = Switching frequency

where, Δi_1 is the as input current ripple on the PV side and it is taken as 10% of the input current and ΔV is known as the output voltage ripple and is taken as the 5% of the output voltage on the load side and

The DC-DC boost converter’s is given by equation

$$D = 1 - \frac{V_{in}}{V_b} \tag{3.7}$$

Where V_{in} is the input voltage for converter from PV side and it is same as V_{pv} and V_b is the output voltage of the converter and is same as load voltage.

CHAPTER 5

GRID CONNECTED SOLAR PHOTOVOLTAIC (SPV) SYSTEM INCORPORATING LOAD HARMONIC COMPENSATION

5.1 GENERAL:

The energy demand is increasing and to meet this demand, distributed energy resources (DERs) can be integrated to the grid. In this chapter, SPV power generating system is integrated to the grid as a DER. Different techniques are used to control and synchronize the SPV system to the grid and this chapter focuses on synchronous reference frame theory (SRFT) based algorithm. Results for different conditions such as linear/non-linear load changes are obtained.

5.2 GRID CONNECTED SOLAR PHOTOVOLTAIC (SPV) SYSTEM:

A MPPT controller is required in order to enhance the performance of the PV system as the capital cost is very much high for installation. PV generation plants can be tied with the grid to get a lowest failure rate and utilize its availability at its maximum. There can be various design modes or applications for the plants based on the PV generation. Two main design schemes are most widely used, first as standalone system with storage support and second as grid tied application with infinite storage support.

The main components of grid connected PV generation plants are PV arrays, PV inverter, the control using algorithms such as the MPPT and inverter current controller etc. The block diagram representation of grid connected solar PV system is shown in Figure 5.1

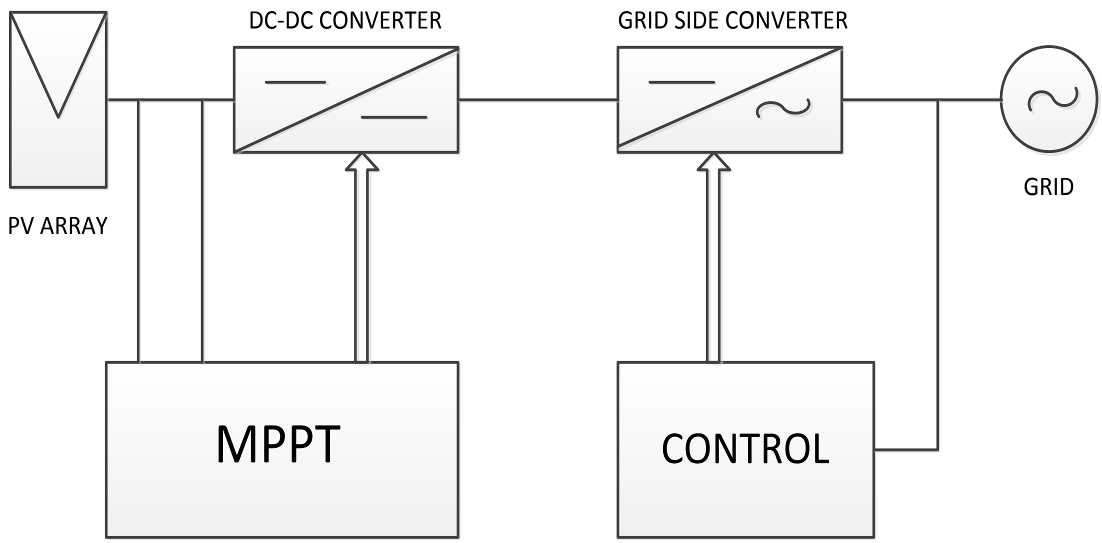

Figure 5.1: Block diagram of grid connected PV system

The integration of solar PV system to the grid creates various effects on quality of power that is supplying to the grid. These issues include voltage fluctuations, harmonics, reactive power, low power factor (PF), load management etc. Therefore an integration of solar PV system to the utility grid should meet the standards of power quality requirements. Solar PV generation is mainly developed in standalone mode or isolated mode and the main drawback of the isolated mode is that it is limited to very low rating of power generation. Also, it requires very large storage capacity; but in recent years the focus is also shifting to grid connected solar PV generation to augment the grid capacity.

The use of voltage source inverter as interfacing units for grid integration applications of PV systems has been investigated extensively in the last few years. There are two main types of VSI which are most widely used namely two level and multilevel VSI. Regardless of the demerits such as high switching losses with low quality output voltage waveforms, the two level VSIs are most widely used.

Generally a photovoltaic grid connected system can be divided in two stages. The first stage is a DC/DC converter which acts as a controller so that the photovoltaic system operates optimally to achieve its maximum power point (MPP). The second stage is a DC/AC converter that is controlled in a way that allows PV to be grid connected. For grid tied PV systems it is very essential to control power flow between the PV and the grid. It is necessary for high power tracking that this mode should conduct with the current controller scheme.

The current control strategy of the PWM VSI system is one of the most important aspects of the today's power electronics converters. We can categorize current controllers in two main categories: nonlinear controllers with on closed loop PWM current and linear controllers with open loop PWM voltage. Both categories of controllers utilize the inner current feedback loop. In the nonlinear controller, hysteresis current control (HCC) is most widely used for three-phase grid-connected VSI systems.

The hysteresis current controller compensates the current error and produces PWM signals with acceptable dynamic limits. The linear current controller based space vector PWM (SVPWM) is an adequate controller, which compensates the current error either by the proportional-integral (PI) regulator or predictive algorithm in which the compensation and PWM generation can be done separately. The main advantages of this controller are an excellent steady-state response, low current ripple and a pure sinusoidal waveform. Moreover, this SVPWM can help to enhance the behavior of this controller due to its favorable features such as constant switching frequency, optimum switching pattern and excellent DC-link voltage utilization. However, only HCC based controller is used for model simulation.

5.3 SYSTEM CONFIGURATION:

Figure 4.2 shows the schematic diagram of SPV power generating system interconnected to grid. It consists of solar PV panel, maximum power point tracking (MPPT) controller with dc-dc boost converter, a three leg VSC, varying consumer loads and utility grid. The dc-dc boost converter is used to boost the voltage level of SPV to feed the power to the dc link. Acceptable power quality standards are to be maintained while integrating renewable energy sources to the electric grid.

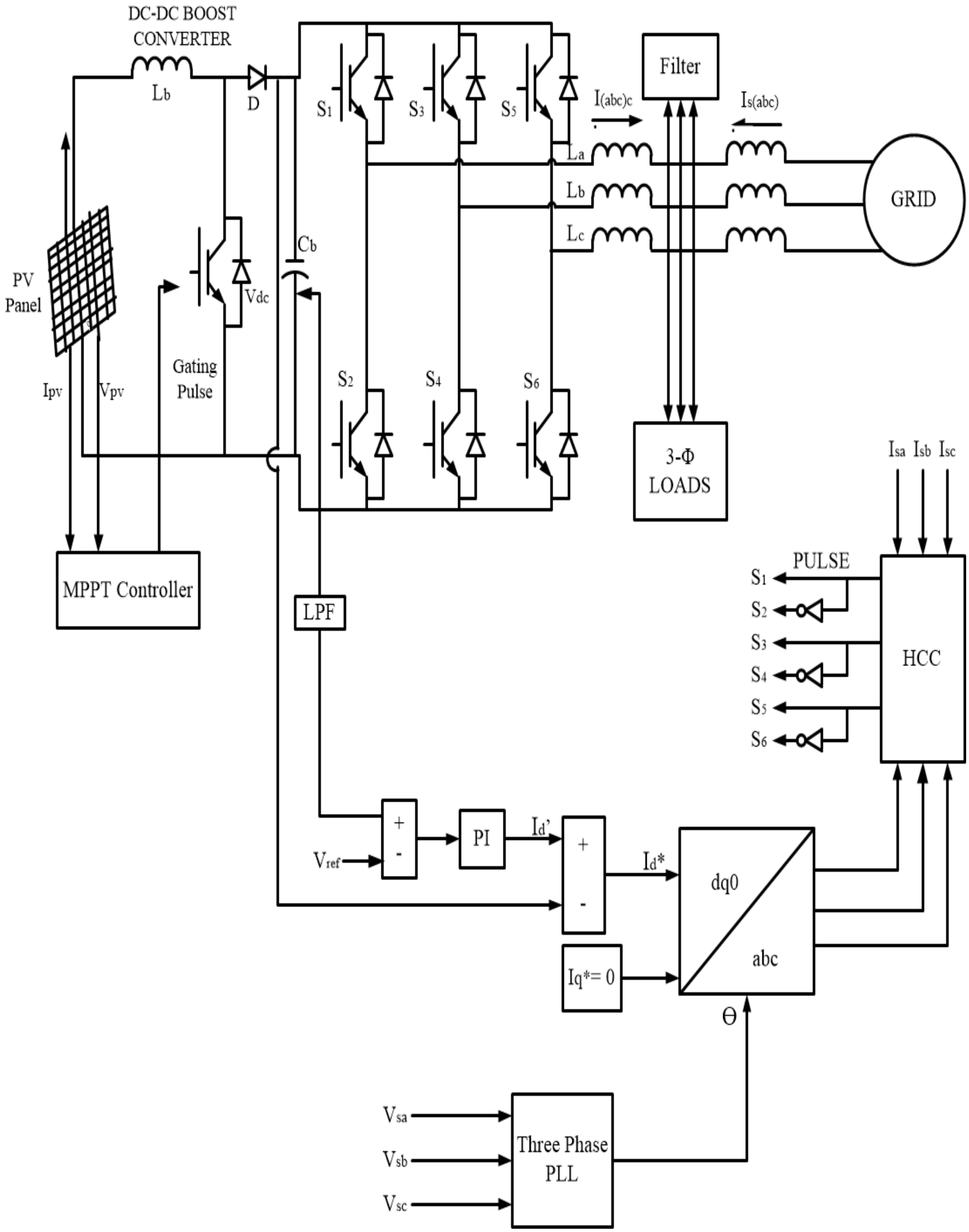

Figure 5.2: Schematic diagram of grid connected SPV system using SRFT control algorithm

The grid interconnected SPV power generating system considered as a two stage grid connected converter. As shown in Fig. 4.2, two stages are shown. The first stage consists of DC-DC converter with maximum power point tracking (MPPT) so that SPV extracts maximum power using MPPT algorithm. The second stage is DC-AC converter i.e. insulated gate bipolar transistor (IGBT) based voltage source converter (VSC). The basic control for VSC is to utilize entire power generated from SPV power source, provide necessary compensation and achieve load balancing. Both the DC-DC & DC-AC converters should operate independently.

In this system, the dc link voltage of SPV and VSC is 700V and to regulate the dc link voltage, a dedicated dc voltage PI controller is used. Ripple filter for the proposed system consists of capacitor connected in delta. The system is controlled in a way to compensate reactive power for load balancing and harmonics elimination. The control algorithm is developed to evacuate all the generated power from SPV generating system.

5.4 DESIGN AND SELECTION OF COMPONENTS:

5.4.1 Selection of DC link Capacitor voltage:

The DC link capacitor voltage of VSC is given by equation 4.1

$$V_{dc} = \frac{\left(2\sqrt{2}\, V_{LL}\right)}{\sqrt{3}\, m} \tag{5.1}$$

Where V_{LL} is the line to line voltage and m is modulation index. It can be inferred that the dc link voltage should be greater than twice of the peak of the phase voltage of the system. For the system considered under investigation, DC link voltage is selected as 700V for modulation index of 0.9 and V_{LL} is 415 volt.

5.4.2 Design & Selection of DC link Capacitor:

Three different criteria used to select and design DC link capacitor only. DC link capacitor design value could be based on dc-dc boost converter. This is already discussed in boost converter design in previous chapter. The value of dc link capacitor based on this method is calculated to be 3500μF. The other two criteria are based on ripple current and energy conservation principle, discussed below.

5.4.2.1 DC link Capacitor based on Ripple Current:

The value of DC link capacitor is given by equation 4.2 for load balancing of the consumer loads by VSC

$$C_d = \frac{I_d}{2 * \omega * V_{dcripple}} \tag{5.2}$$

Where I_d is the dc link current, ω is angular frequency and $V_{dcripple}$ is 5% of the dc link voltage of VSC. The value of dc link current is calculated under when one phase load removal i.e. 2/3 I_d or 33% of load current is reduced by removing one phase of load. The value of dc link capacitor based on ripple current method is calculated as 1200μF.

5.4.2.2 DC link Capacitor based on Energy Conservation Principle:

The design of DC link capacitor (Cd) of VSC depends upon the instantaneous energy available to the VSC at the time of transient. Based on the principle of energy conservation principle, the value of DC capacitor is given below

$$\frac{1}{2} C_d \left[V_{dc}^2 - V_{dc1}^2\right] = 3V\alpha It \tag{5.3}$$

Where V is the phase voltage, I is the phase current, t is the time by which dc link voltage is to be recovered, V_{dc} is the reference DC link voltage and V_{dc1} is the minimum DC link voltage level of DC bus. Taking, V_{dc} = 700 V, V_{dc1} = 690 volt, α= 1.2, t=350 microsecond, the calculated value of Cd is obtained to be 1500 μF.

5.4.3 Design of AC Inductors:

The selection of ac inductance (L_{abc}) of VSC depends upon the different parameters like the ripple current Δi, switching frequency fs, modulation index (m), dc link voltage (V_{dc}) and L_f is given by

$$L_f = \frac{\sqrt{3} m V_{dc}}{12 h f_s \Delta i} \tag{5.4}$$

Taking, m =0.9, h =1.2, α= 1.2, t=350 microsecond.

5.5 CONTROL ALGORITHM:

Different control algorithms are mentioned in literature like synchronous reference frame theory (SRFT), instantaneous reactive power theory (IRPT) etc. Synchronous reference frame theory (SRFT) is implemented in this chapter and it is used to control the SPV power generating system. Insulated gate bipolar transistor (IGBT) based VSC is used and the dc bus of SPV and VSC is controlled and maintained to a reference voltage in order to provide compensation for the load currents through SPV power.

5.5.1 Synchronous Reference Frame Based Grid Synchronization Technique:

SRF theory is related to extraction of synchronously rotating d-q components of current from 3-phase load current. Basic diagram for this theory is shown above. Controller is the basic building block of this algorithm. Controller takes source voltage and load current as input. Phase locked loop (PLL) tracks the phase of input voltage signal and generate unit voltage templates (sine and cosine components). These d-q components of currents passed by a filter which filter out high frequency harmonic components. Then again d-q frame is transformed back to 3-phase components. This current is then compared with source current and error between them is fed to Hysteresis-based PWM signal generator to produce final switching signals which are the pulses for voltage source converter.

System terminal voltages are given as,

$$V_{sa} = V_m \sin(\omega t) \tag{5.5}$$

$$V_{sb} = V_m \sin\left(\omega t - {}^{2\pi}/_{3}\right) \tag{5.6}$$

$$V_{sc} = V_m \sin\left(\omega t + {}^{2\pi}/_{3}\right) \tag{5.7}$$

And load current are given as:

$$i_{La} = I_m \sin(\omega t - \theta_n) \quad (5.8)$$

$$i_{Lb} = I_m \sin\left(\omega t - {}^{2\pi}/_{3} - \theta_n\right) \quad (5.9)$$

$$i_{Lc} = I_m \sin\left(\omega t + {}^{2\pi}/_{3} - \theta_n\right) \quad (5.10)$$

Using equation (1), Current components in $(\alpha - \beta)$ coordinates are calculated. Then using θ,

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -{}^{1}/_{2} & -{}^{1}/_{2} \\ 0 & {}^{\sqrt{3}}/_{2} & -{}^{\sqrt{3}}/_{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (5.11)$$

Calculated from PLL as transformation angle converted $(\alpha - \beta)$ to $(d - q)$ frame. After this, filter is used to remove dc component from the currents, then $(d - q)$ component of current is converted to $(\alpha - \beta)$, equation (2),

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5.12)$$

And from $(\alpha - \beta)$ to a-b-c, equation

$$\begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} {}^{1}/_{\sqrt{2}} & 1 & 0 \\ {}^{1}/_{\sqrt{2}} & -{}^{1}/_{2} & {}^{\sqrt{3}}/_{2} \\ {}^{1}/_{\sqrt{2}} & -{}^{1}/_{2} & -{}^{\sqrt{3}}/_{2} \end{bmatrix} \quad (5.13)$$

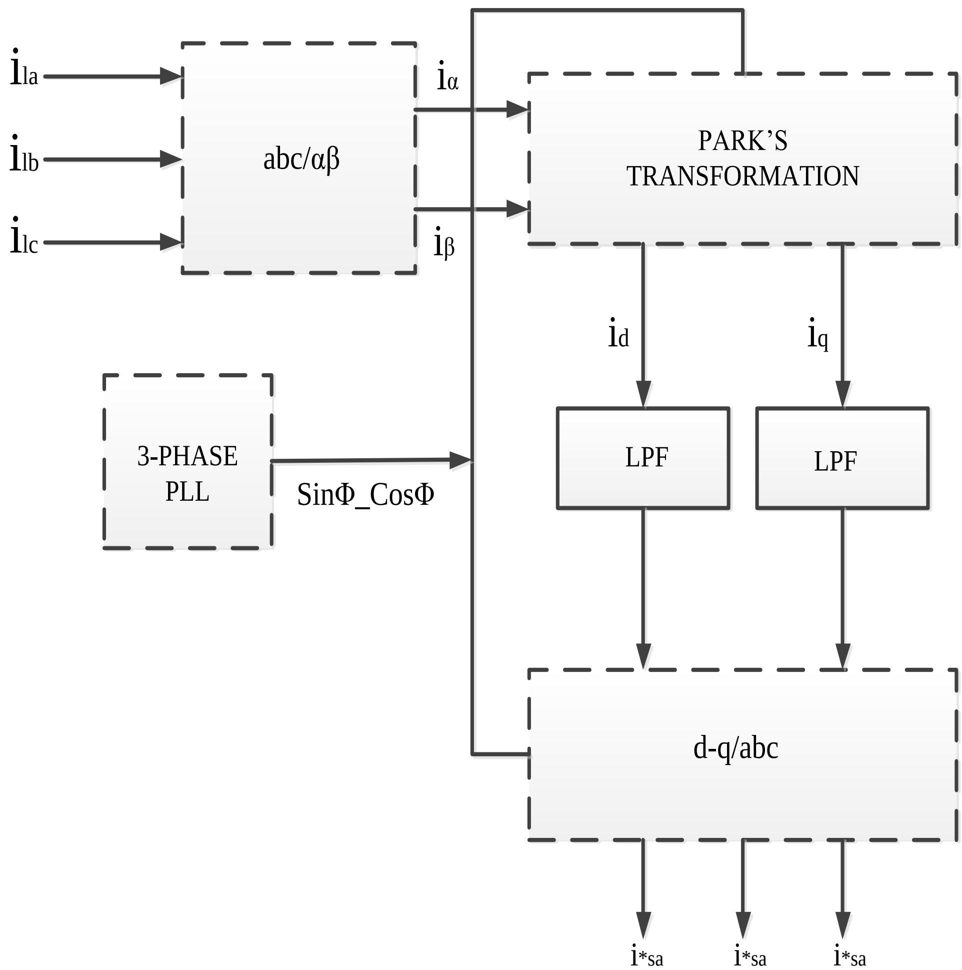

Fig: 5.3 Reference current extraction using SRF theory

These are reference current generated. These reference currents are compared with actual current and error between both will be the required amount of reactive current supplied by VSC. Error of current is used to generate pulses for inverter. Inverter is equipped with a capacitor, which supplies necessary reactive power to the system.

5.6 RESULTS AND DISCUSSION:

5.6.1 For Linear Load:

Case 1: For Resistive (R) load

Performance of developed three phase grid connected PV system has been analyzed for a linear load of 30 KW. Solar Photovoltaic Array modelled in this work is of 20 KW. A MPPT technique is employed in order to observe the performance of the system for varying irradiance inputs. PV array characteristics are shown in figure 5.4.

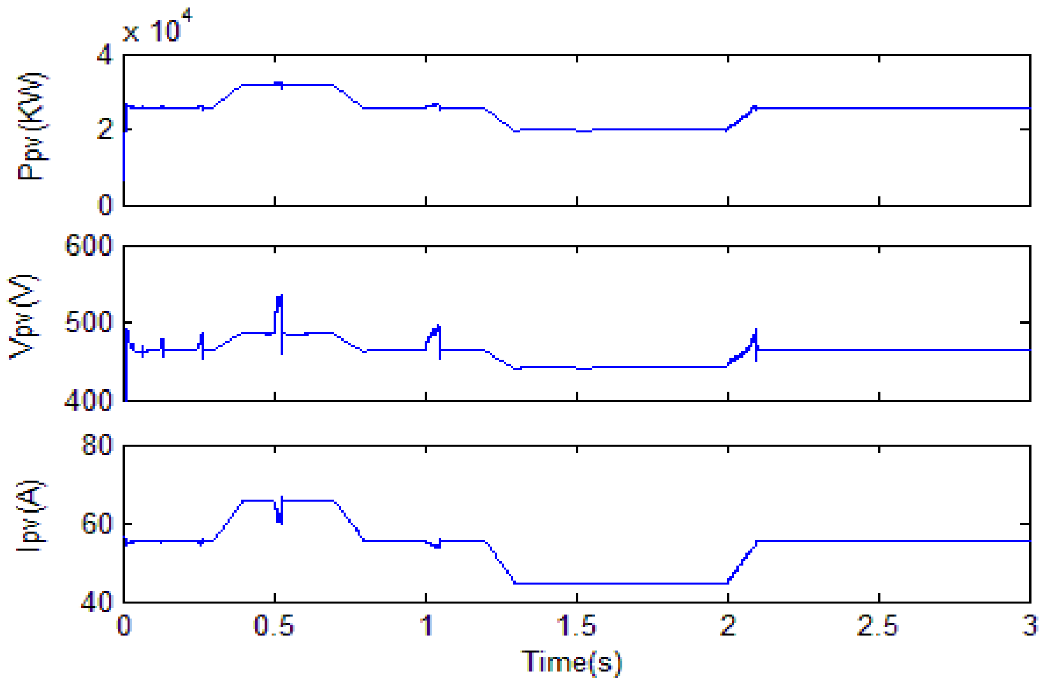

Fig 5.4: Characteristics of PV array

At the starting of the system it is assumed that the ambient conditions are same as STC (standard test condition). At 0.3 sec the irradiance is increased at 1200 W/m^2, it can be observed that the output of PV array increased beyond its MPP. Again at 0.7 sec, the irradiance level is reduced to 1000W/m^2. At 1.2 sec, the irradiance is further reduced to a value of 800W/m^2 which reduced the output of PV array. At 2 sec, the irradiance is again kept at 1000W/m^2 which increased the output of PV array.

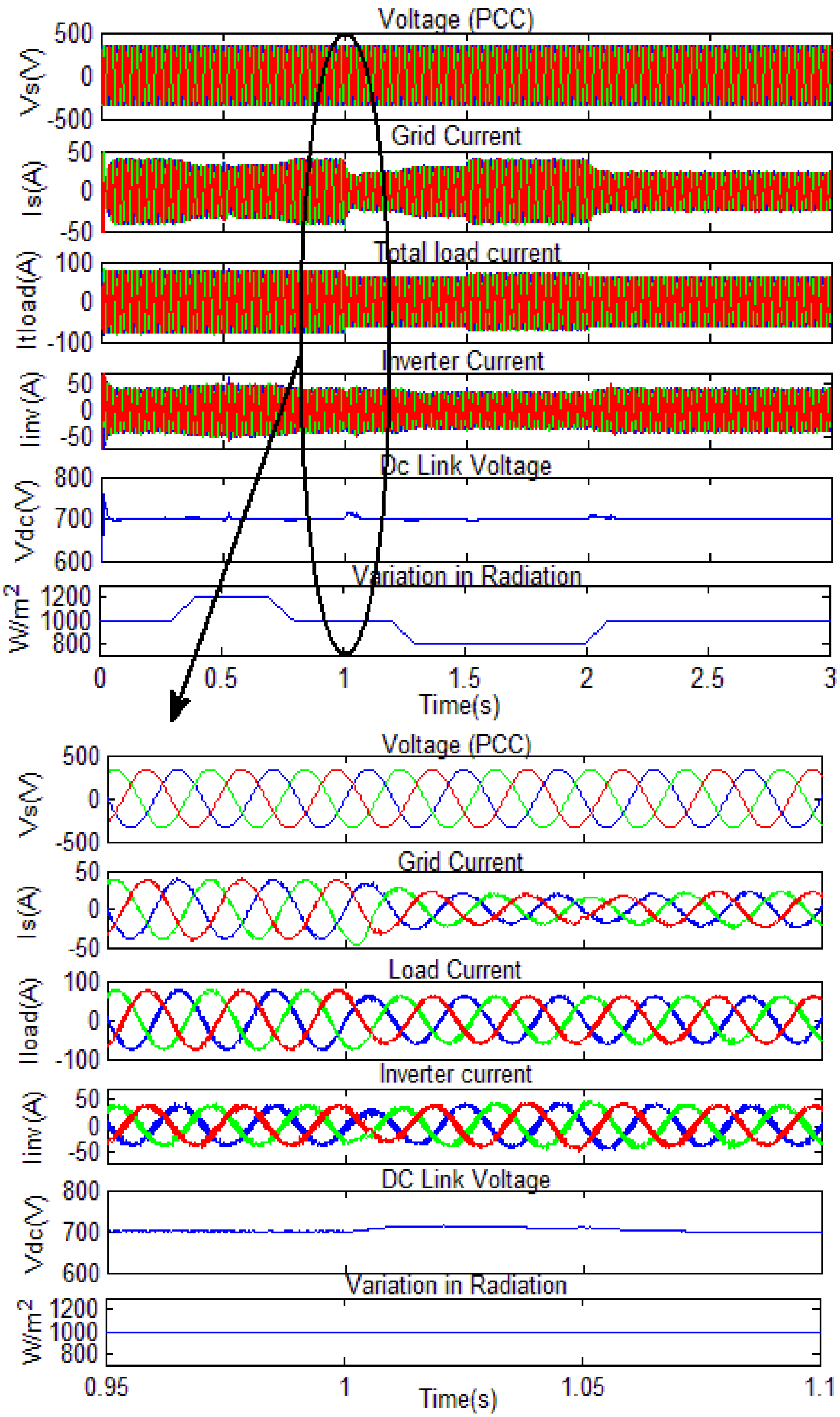

Fig: 5.5 Voltage and current Waveforms of Grid, Load and Inverter with the radiation in R load Condition

Figure 5.5 shows the waveforms of the Grid voltages, Grid currents, load currents, inverter currents, dc-link voltage and variation in radiation. In this simulation the load change and variation in radiation are done for different time of interval. The load is varied by disconnecting the load at 1 sec whereas another load is connected at 1.5 sec. The zoomed view around 1 sec is shown for various waveforms, in order to validate that the power generated from PV panel is being injected at unity power factor w.r.t grid voltage. It can also be seen from the waveforms that the magnitudes of the load current as well as the source current are reduced, but the inverter current magnitude is remains same because it depends upon the solar radiation. The dc link voltage is slightly overshoots due to reduced load current but it maintains the dc link voltage again to its reference value i.e. 700V in 2cycles. During this the radiation is kept constant as 1000W/m^2.

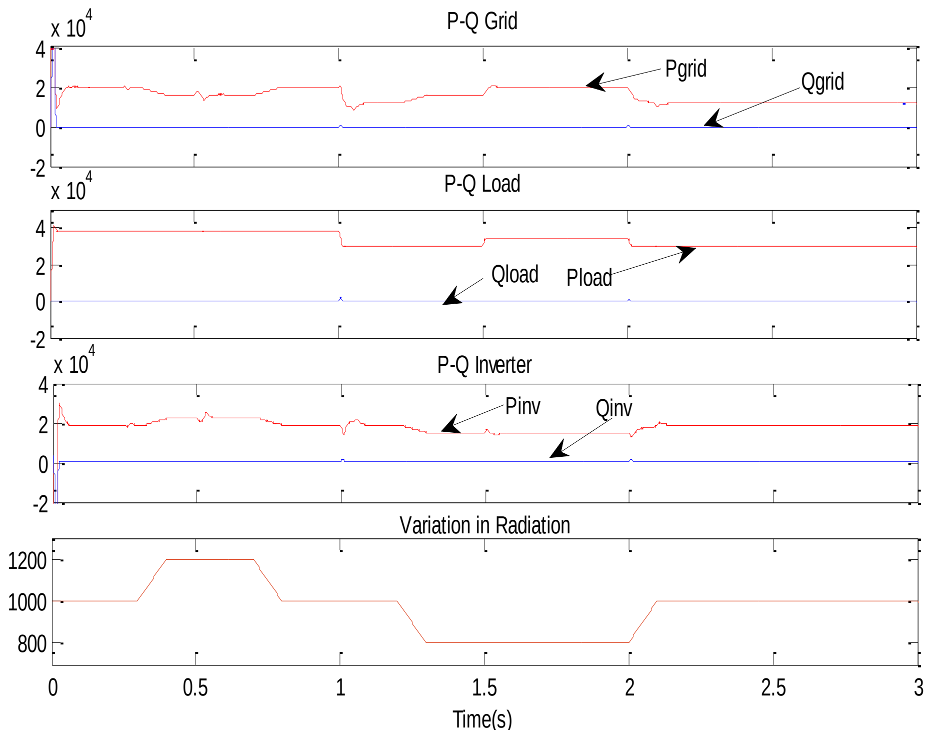

Fig: 5.6 Active and Reactive Powers of Grid, Load and Inverters with the radiation in R Load Condition

Figure 5.6 shows the waveforms of the active power and reactive powers of Grid, Load and Inverter with the variation of solar radiation. In this case the active power requirement is shared between the both Grid and the Solar PV system. Here only resistive load is connected so the reactive power flow is zero.

Case 2: For R-L load:

In this section the simulation study has been carried out for proposed Grid connected PV system with 3-phase R-L load. Here the main purpose of this simulation study is to control the grid interfacing inverter in such a way that it not only injects the Generated power into grid but also compensates the load reactive power requirement so that the grid always keep on working at unity power factor.

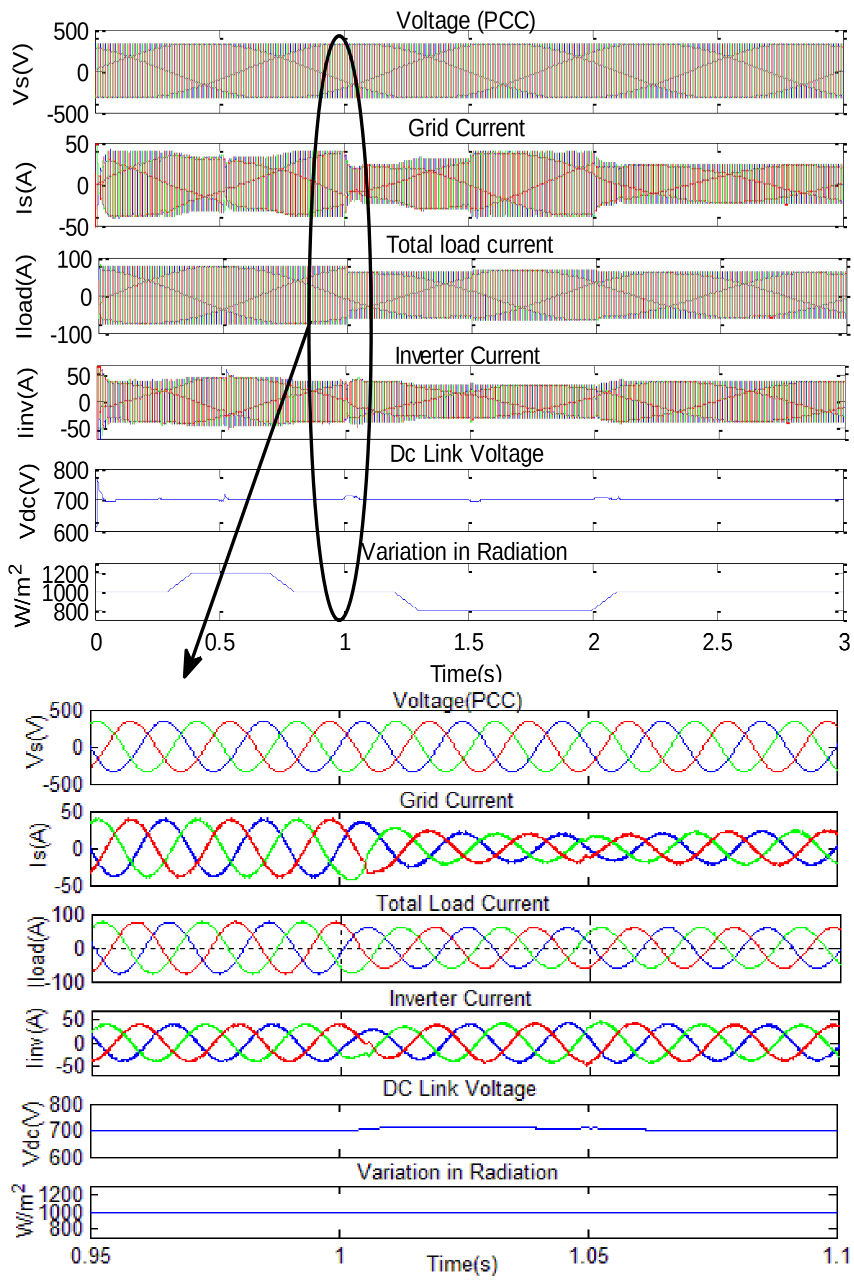

Fig 5.7 Voltage and current Waveforms of Grid, Load and Inverter with the radiation in R-L load Condition

Figure 5.7 shows the waveforms of the Grid voltages, Grid currents, load currents, inverter currents, dc-link voltage and variation in radiation. Referring to Figure 5.7, here in between the simulation time of 1 sec to 1.05 sec, the load has been changed. At the instant of simulation time of 1sec, a load of 8 kW has been removed, the load current has been reduced and subsequently there is a slight variation in DC link voltage with constant solar irradiance.

From the waveforms shown above, it has been observed that the load current having inductive component lagging the voltage and grid current is at unity power factor. Reactive power compensation can be performed upto the thermal rating of inverter. During the transient time, it is shown that grid current always remains in phase with voltage without any harmonic distortion. Under solar insolation variation, the grid current and grid voltage at the different loads viz. R and R-L load, is purely sinusoidal and are in phase under reactive compensation condition.

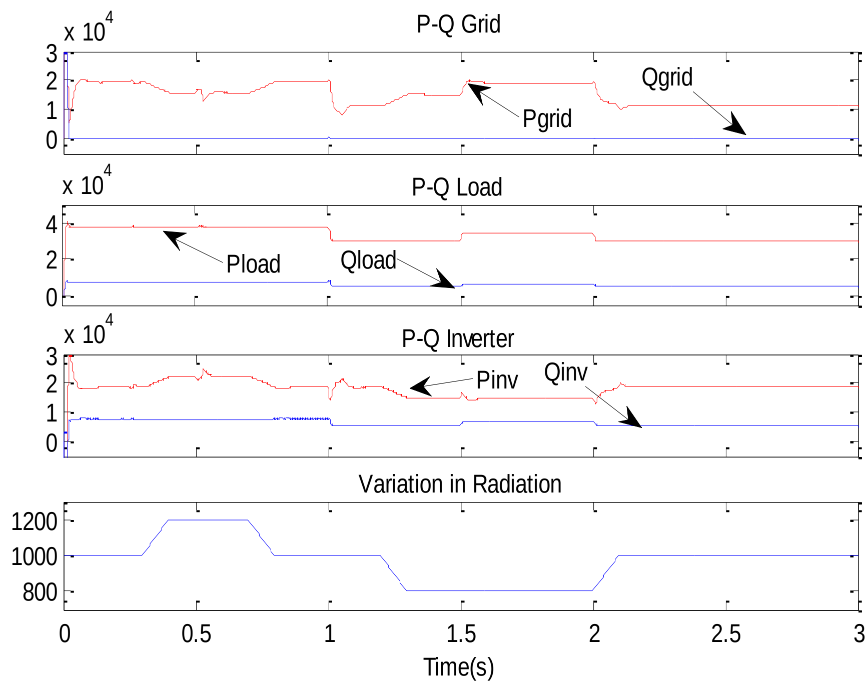

Fig 5.8 Active and Reactive Powers of Grid, Load and Inverters with the radiation in R-L Load Condition

Figure 5.8 shows the waveforms of the active power and reactive powers of Grid, Load and Inverter with the variation of solar radiation. In this simulation, the active power requirement of the load is fulfilled by both the Grid and the Solar PV system. Inverter supplies its maximum amount of active power to the load and only deficit amount of active power is supplied by the Grid. The grid supplying no reactive power and the whole reactive power requirement of the load is fulfilled by Solar PV system so in the proposed work, the Reactive Power Compensation has been done at the Grid working at unity power factor.

5.6.2 For Non-Linear Load:

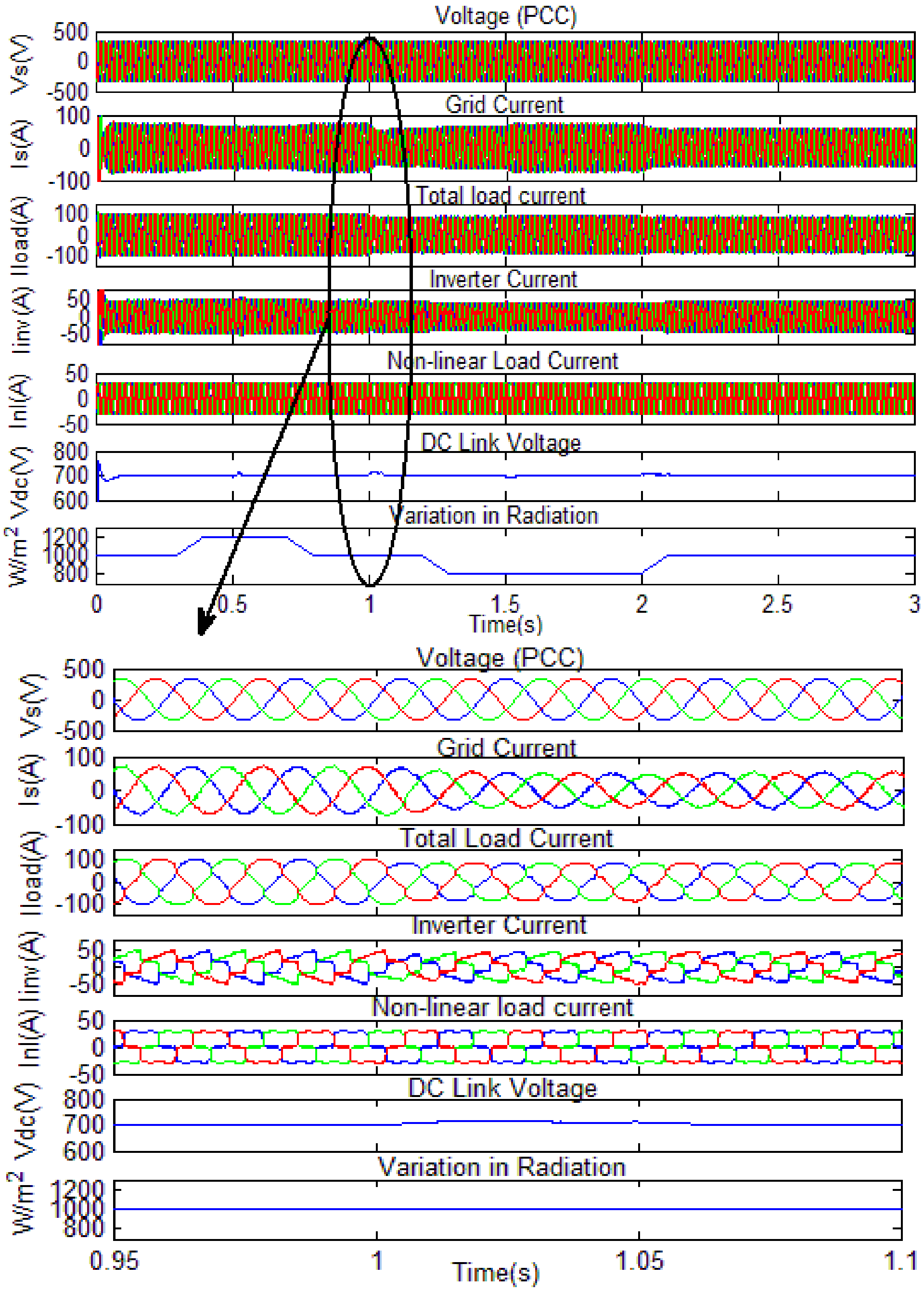

Fig 5.9: Voltage and current Waveforms of Grid, Load and Inverter with the radiation in Non-linear load Condition

Figure 5.9 shows the waveforms of the Grid voltages, Grid currents, total load currents, inverter currents, non-linear load currents, dc-link voltage and variation in radiation. In this section the simulation study has been carried out for Grid connected PV system with both linear and non-linear load. In this, the load change and variation in radiation are done for different time of interval. Referring to Figure 5.9, here in between the simulation time of 1 sec to 1.05 sec, the load has been changed. At the instant of simulation time of 1sec, a load of 8 kW has been removed, the load current has been reduced and subsequently there is a slight variation in DC link voltage with constant solar irradiance.

The zoomed view around 1 sec is shown for various waveforms, in order to validate that the power generated from PV panel is being injected at unity power factor w.r.t grid voltage. It can also be seen from the waveforms that the magnitudes of the load current as well as the source current are reduced, but the inverter current magnitude is remains same because it depends upon the solar radiation. During this the radiation is kept constant as $1000W/m^2$. The simulation study shows control of grid interfacing inverter in such a way that it injects the Generated power into grid and compensates both the load harmonic power and the load reactive power requirement so that the grid always keeps on working at unity power factor.

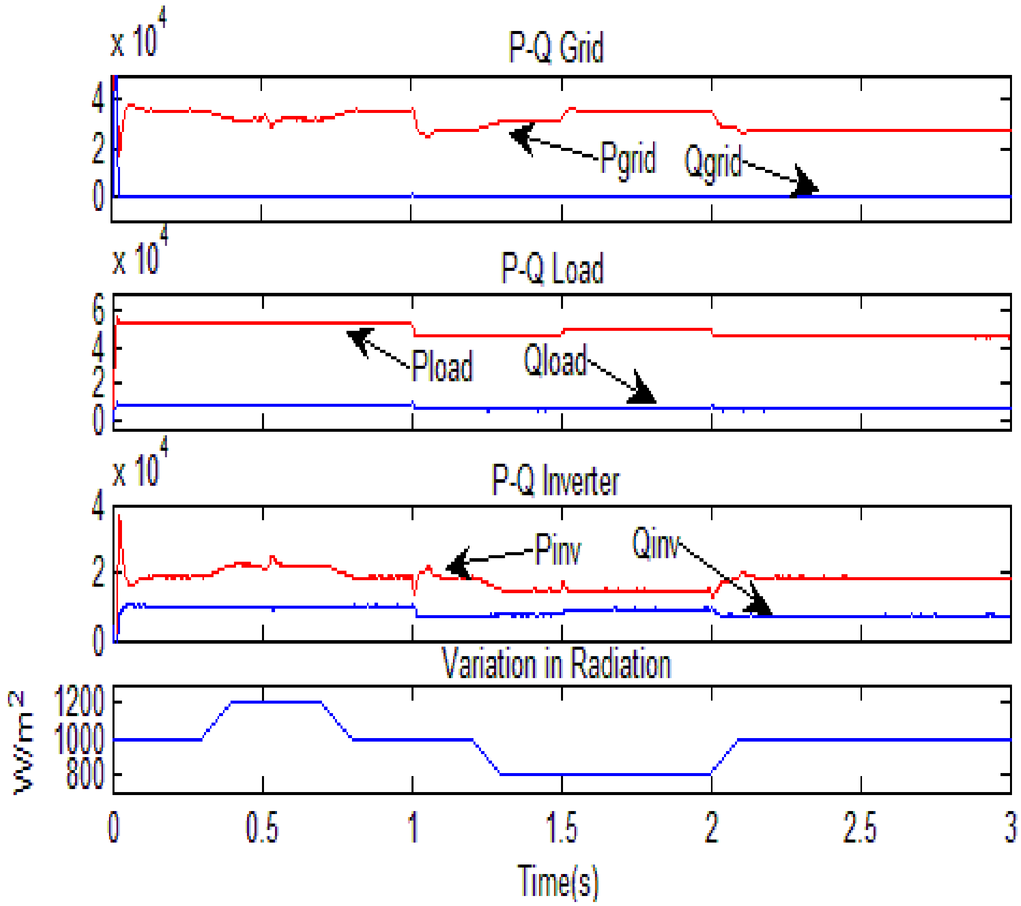

Fig 5.10 Active and Reactive Powers of Grid, Load and Inverters with the radiation in Non-linear Load Condition

Figure 5.10 shows the waveforms of the active power and reactive powers of Grid, Load and Inverter with the variation of solar radiation. In this case the active power requirement is shared between both Grid and the Solar PV system. The whole reactive power requirement of the load is fulfilled by Solar PV system. So the Reactive Power compensation and the load Harmonic Compensation are done in this proposed work and the Grid always keeps on working at unity power factor.

From the FFT analysis of non-linear load current it is found that this current has THD of 28.19% while The Grid current FFT analysis shows that it has only 1.84% THD which is very low. The FFT analysis of Grid current and Non-linear load current are shown in figure 5.11 and 5.12 respectively.

Non-linear Load Current FFT Analysis:

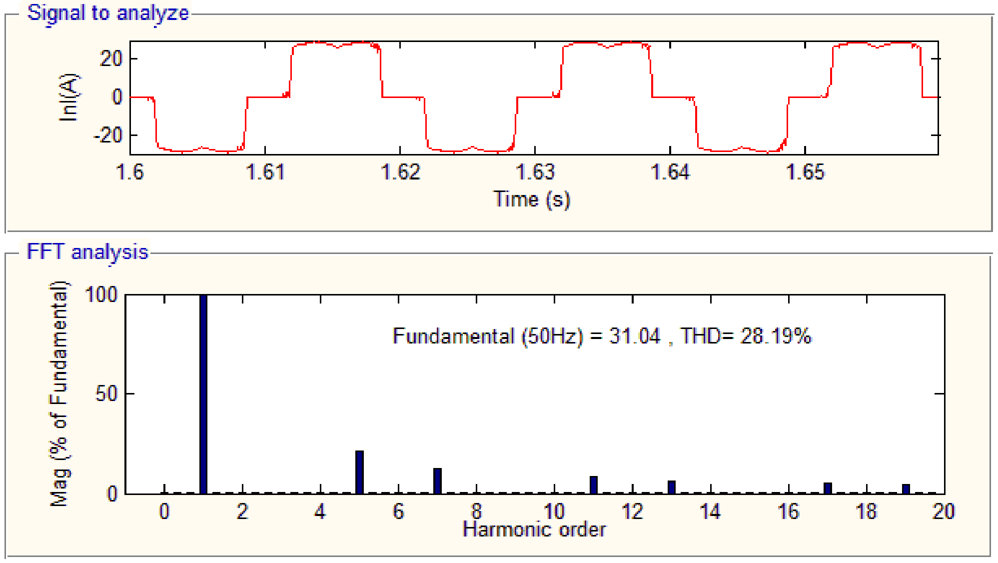

Fig: 5.11 FFT Analysis of Non-linear Load current

Grid Current FFT Analysis:

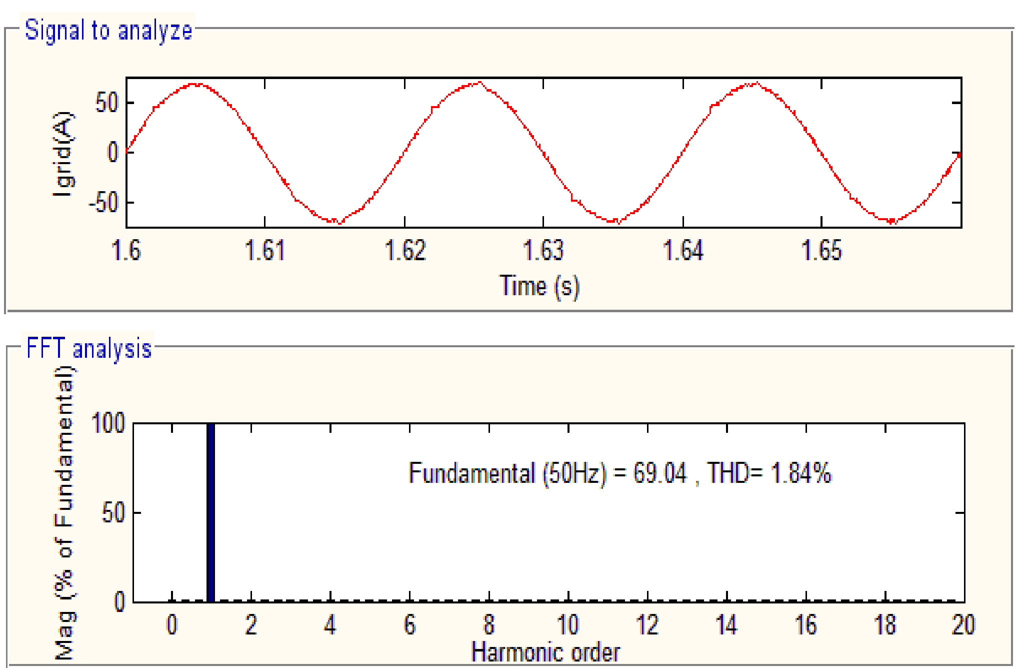

Fig: 5.12 FFT Analysis of Grid current for non-linear load

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF WORK

6.1 CONCLUSION:

The characteristics of PV have been successfully obtained for different conditions of irradiation levels. P&O MPPT algorithm has been modeled and simulated in order to maximize the output of PV array near its maximum power point. A DC/DC boost converter is designed to implement the MPPT algorithm. Constant power is maintained at the input and output side of the converter with slight difference due to switching losses, irrespective of the load change. The grid integrated SPV system performance is investigated and analyzed successfully for different conditions like linear and non-linear load. Complete reactive power compensation with reduced load harmonics are achieved by using synchronous reference frame theory (SRFT) algorithm. The DC bus voltage and terminal voltage of PCC voltage are maintained at desired level for steady state and dynamic load variation. This work mainly deals with the integration of PV plant to grid and development of control algorithm for improving the power quality of the grid. Results are presented for both types of loads namely linear and nonlinear. This thesis provides the detail design of PV array, boost converter, MPPT algorithm and control of grid integration with three phase utility grid.

6.2 FUTURE SCOPE OF THE WORK:

The work done in thesis can be extended in future:

- Different control schemes can also be implemented in future for synchronization of PV system with the three phase utility grid.
- A hardware implementation can be done for the proposed system for performing the various experiments and power quality analysis can also be done.

REFERENCES

[1] Subarto Kumar Ghosh, Mohammad Hasanuzzaman Shawo, Ashifur Rahman and Rifat Abdullah, " Modeling of PV Array and Analysis of Different Parameters" International Journal of Advancements in Research & Technology, Volume 2, Issue 5,pp-358-363 , 2013.

[2] R.Chedid, R.Tajeddine and F. Chaaban, "Modeling and Simulation of PV Arrays under Varying Conditions" 17th IEEE Mediterranean Electrotechnical Conference, Beirut, Lebanon, pp-536-542, 2014.

[3] Tom. Markvart and Luis Castañer, "Principles of Solar Cell Operation" (book).

[4] Huiying Zheng, Shuhui Li, Ke Bao, and Dong Zhang, "Comparative Study of Maximum Power Point Tracking Control Strategies for Solar PV Systems".

[5] Trishan Esram, Patrick L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques" IEEE Transactions On Energy Conversion, Vol. 22, No. 2, pp-439-449, June 2007.

[6] Moein Jazayeri, Sener Uysal, "Evaluation of Maximum Power Point Tracking Techniques in PV Systems using MATLAB/Simulink" Sixth Annual IEEE Green Technologies Conference, pp-54-60, 2014.

[7] D. S. Karanjkar, S. Chatterji and Shimi S. L, "Real Time Simulation and Analysis of Maximum Power Point Tracking (MPPT) Techniques for Solar Photo-Voltaic System" RAECS UIET Panjab University, 2014.

[8] Dr. Tilak Thakur, Kuldeep Singh Bedi, "Data Based MPPT Technique for Photovoltaic System".

[9] Ahmed S. Khalifa, Ehab F. El-Saadany, "Control of Three Phase Grid Connected Photovoltaic Power Systems".

[10] Atiqah Hamizah, Mohd Nordin,Ahmad Maliki Omar, "Modeling and Simulation of Photovoltaic (PV) Array and Maximum Power Point Tracker (MPPT) for Grid-Connected PV System" 3rd International Symposium & Exhibition in Sustainable Energy & Environment, pp-114-119, 2011.

[11] M.Makhlouf , F.Messai, K.Nabt1 and H.Benalla, "Modeling and Simulation of Grid-connected Photovoltaic Distributed Generation System" First International Conference on Renewable Energies and Vehicular Technology,pp-187-193, 2012.

[12] Bhim Singh, D. T. Shahani, Arun Kumar Verma, "Power Balance Theory Based Control of Grid Interfaced Solar Photovoltaic Power Generating System with Improved Power Quality" IEEE International Conference on Power Electronics, Drives and Energy Systems, 2012.

[13] Sidharth Rajamohan, ChelladuraiVignesh, "Modelling of Solar Array and Design of a Vector based Dual Band Hysterisis Current Control Technique for a 3 Phase Grid Connected PV system" International Conference on Emerging Trends in Science, Engineering and Technology, pp-437-442, 2012.

[14] Rajan Kumar, Asit Mohanty, S.R.Mohanty, Nand Kishor, "Power Quality Improvement in 3-Φ Grid Connecte Photovoltaic System with Battery Storage" IEEE International Conference on Power Electronics, Drives and Energy Systems, 2012.

[15] Fei Liu, Yan Zhou, Jinjun Yin, Shanxu Duan, "An Improved MPPT Arithmetic and Grid-connected Control Strategy for Single-Stage Three-Phase PV Converter with LCL Filter" pp-808-813, 2008.

[16] Lakshmanan.S.A, B. S. Rajpourhit, "Modeling and Analysis of 3-Phase VSI using SPWM Technique for Grid Connected Solar PV System" IEEE Students Conference on Electrical, Electronics and Computer Science, 2014.

[17] K K Prajapat, Abhishek Katariya, Ashok Kumar, Shuchi Shukla, "Simulation and Testing of Photovoltaic with Grid Connected System" International Conference on Computational Intelligence and Communication Systems, pp-692-697, 2011.

[18] Nidhi Agarwal,"Design and Simulink of Intelligent Solar Energy Improvement with PV Module" International Journal of Information & Computation Technology, Volume 4, Number 6, pp-619-628, 2014.

[19] Ahmed M. Atallah, Almoataz Y. Abdelaziz, And Raihan S. Jumaah, “Implementation Of Perturb and Observe Mppt Of Pv System with Direct Control Method Using Buck And Buckboost Converters.

[20] Kun Ding, XinGao Bian, HaiHao Liu, and Tao Peng, “A MATLAB-Simulink-Based PV Module Model and Its Application Under Conditions of Non-uniform Irradiance” IEEE Transactions On Energy Conversion, Vol. 27, No. 4, 2012.

[21] Liming Liu, Yan Zhou, Hui Li, “Coordinated Active and Reactive Power Management Implementation Based on Dual-stage PLL Method for Grid-connected PV System with Battery” pp. 328-335, IEEE 2010.

[22] M. G. Molina, P. E. Mercado, “Modeling and Control of Grid-connected Photovoltaic Energy Conversion System used as a Dispersed Generator” IEEE, 2008.

[23] Wu Libo, Zhao Zhengming, Liu Jianzheng, “A Single-Stage Three-Phase Grid- connected Photovoltaic System With Modified MPPT Method and Reactive Power Compensation” IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 22, NO. 4, 2007.

APPENDIX

A. Parameters for 20 KW Solar Photovoltaic System:

Number of Cells in Series (N_s) = 1072

Number of Cells in Parallel (N_p) = 18

Parallel Series Resistance = 400 ohm

Voltage at P_{max}= 600V

Current at P_{max}= 55.4A

B. Parameters for DC-DC Boost converter

Inductance (L) = 500 µH,

Capacitance (C) = 2000 µF

Switching frequency = 20 KW

C. Parameters for VSC

DC bus voltage: 700V

DC bus Capacitance: 5000 µF

AC line voltage: 415V, 50Hz

Modulation index: 0.9

Linear load: 30kVA

Non-linear load: Three phase bridge rectifier with R = 20 Ω and L = 10mH