GRID INTEGRATION OF SOLAR PV SYSTEM

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
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Submitted by:

Sakshi Gangwar

2K18/C&I/15

Under the supervision of
Prof. Madhusudhan Singh

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2020

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I, Sakshi Gangwar, Roll No. 2K18/C&I/15 student of M.Tech. Control and Instrumentation (C&I), hereby declare that the dissertation/project titled **"GRID INTEGRATED PV SYSTEM USING A SIMPLE PI CONTROLLER AND POWER BALANCE THEORY"** under the supervision of Prof. Madhusudhan Singh of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology in Control and Instrumentation has not been submitted elsewhere for the award of any Degree.

Place: Delhi

Type text here

(SAKSHI GANGWAR)

Date: 30/11/2020

Prof. Madhusudhan Singh
(SUPERVISOR)
Professor
Department of Electrical Engineering
Delhi Technological University

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SAKSHI GANGWAR

2K18/C&I/15

M. Tech. (Control and Instrumentation)

Delhi Technological University

ABSTRACT

The project aims at design and analysis of a grid connected Solar Photovoltaic (SPV) system which maintains its DC link voltage at appropriate level and deliver the electrical power into grid at unity power factor. A 50kW PV array is designed and connected to the grid through a dc-dc boost converter and voltage source inverter (VSI). The operation of this PV system is demonstrated at varying solar irradiance. When the irradiance is varied, the output power of the PV array also varies and hence a dc to dc boost converter is needed to maintain its output voltage and current conditions in order to obtain the maximum power from PV array at any point of time. This is achieved using maximum power point tracking (MPPT) method. The Perturb and Observe (P&O) algorithm of MPPT is used in the present analysis which helps to maintain the output of the PV array at its maximum operating conditions.

This MPPT algorithm is also implemented using XILINX SYSTEM GENERATOR which makes use of the Xilinx library block set in the MATLAB/simulink environment. It allows design using existing Xilinx blocks or code in verilog or VHDL using black box. It is also possible to write a MATLAB code in m-code block if the input and output and the desired function are known.

The MPPT control is implemented in a dc to dc boost converter that increases the output voltage of the PV array to a higher level. The switching of the MOSFET switch in the Boost converter is controlled by the MPPT algorithm. A VSI is being used to convert DC output power of boost converter into three phase AC power which is delivered to the grid. The VSI

Maintain the DC link voltage at 800V and also deliver three phase AC power at unity power factor to the utility or the grid.

Two control schemes are used in the VSI:

1) A simple PI controller to regulate DC link voltage using the reference current waveform generated using grid voltage. The reference current is compared with actual grid current to generate PWM control signals for switches in VSI.
2) Power balance theory: This technique of inverter control involves generation of reference current waveform using the grid voltage, load current and the DC link voltage. The grid

current is then compared with this generated reference waveform and the PWM signals are generated, which are given to the VSI as the gate pulses.

A complete model of grid tied solar PV system for 50kWp power is developed in MATLAB/Simulink and performance of the system is analyzed under varying solar irradiance level.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In INDIA the total installed capacity of the solar PV systems is about 37.627 GW as of 31 MARCH 2020. Initial target of Indian government was to have 32 GW capacity by 2022, which was reached four years before the scheduled target. In 2015, 100 GW target was set of solar capacity by 2022. Approximately 42 solar parks were established for the solar plants. Within 10 years, up to March 2020, installed capacity of solar power in India increased by many times from 161 MW to 37,627 MW.

70% of the total of 2.1 GW rooftop solar power is industrial or commercial. Solar products have largely fulfilled the rural needs. In 2015 according to a national program 118,700 SPV systems were available for household lightening and 46,655 street lights (solar) were installed.

India has put forward the concept of "One Sun One World One Grid".

There is a need to suitably harness the energy received from the sun because it has the potential to meet all our energy requirements of the future. The sun is an extremely powerful source of energy but the solar energy received by the surface of the earth has a low intensity. This is because of numerous factors, a few of them being the distance of the sun from the surface of the earth, radial spreading of radiation, earth's atmosphere etc.

Fig.1.1 REWA solar power plant

Fig.1.1 shows one of the biggest solar power plants in the world. It is situated in Madhya Pradesh, India. The REWA solar power plant has a total generation capacity of 750MW. It consists of three generating units, each with a capacity of 250MW and the land area of 500-hectares. This plant was set up by the joint venture between Solar Energy Corporation Of India (SECI) and Madhya Pradesh Urja Vikas Nigam Limited. The electricity generated from this plant will be supplied to Madhya Pradesh Power Management Company Limited and the Delhi Metro Rail Corporation (DMRC).

1.2 SOLAR POTENTIAL IN INDIA

In a single year India receives solar irradiance for about 300 days and the total solar radiations incident on the country's land area is calculated to be 5×10^{15} kWh/year. The total available solar energy per year is more than the energy which can be obtained from all the India's fossil fuel energy reserves. The average generation capacity of solar plant in India per day is 0.20 kWh/m^2 of the land area used.

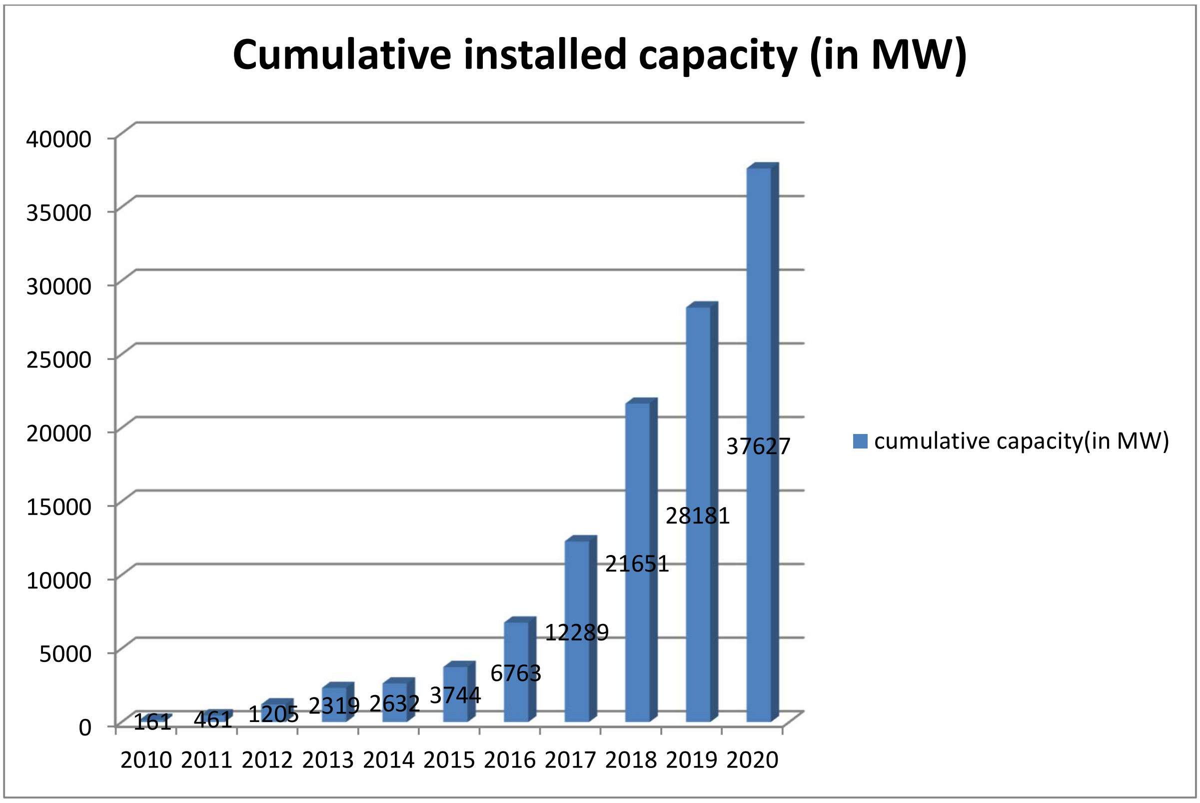

Fig.1.2 Installed solar PV as on 31st March 2020

1.3 SOLAR POWER GENERATION IN INDIA

The total utility generation is 98.76 TWh, and out of this the total solar electricity generation was 3.93 TWh which is 3.98% of the total utility generation.

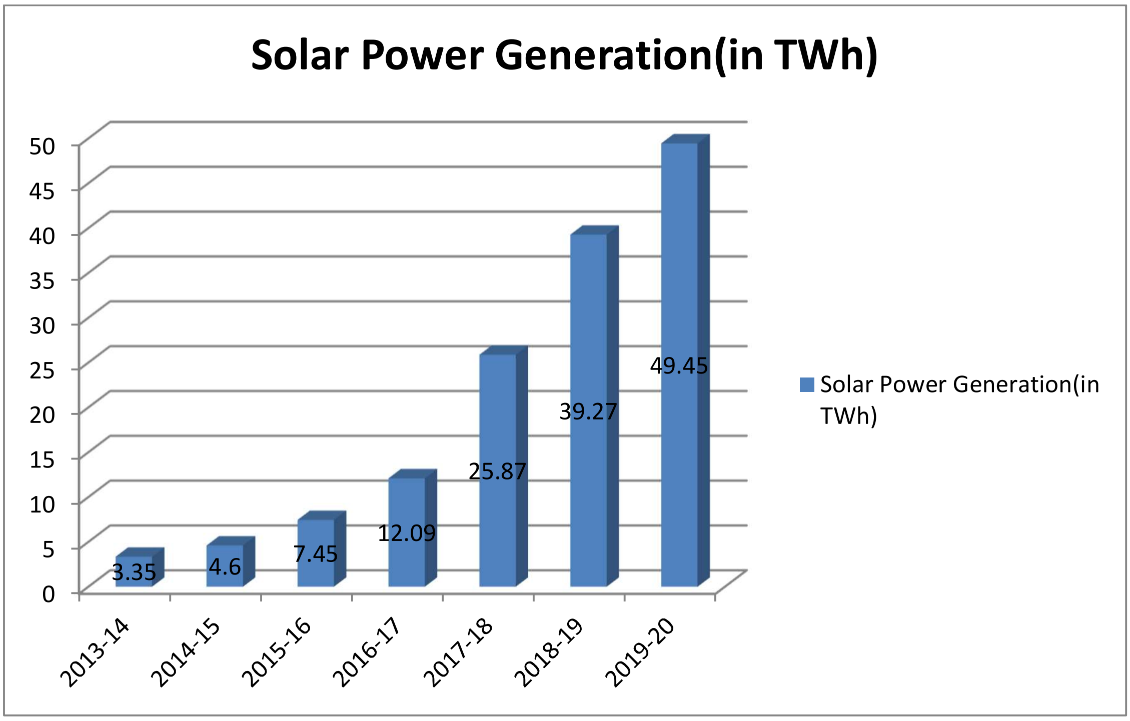

Fig.1.3 Annual solar power generation

TABLE 1.1 SOLAR PHOTOVOLTAICS (PV) INSTALLED CAPACITY BY APPLICATIONS (MW) IN INDIA

Applications	Installed capacity (MW) as on 31/07/2019
GROUND MOUNTED SOLAR POWER	27,930.32
ROOFTOP SOLAR POWER	2,141.03
OFF-GRID OR ISOLATED SOLAR POWER	919.15
TOTAL	30,990.50

Developing countries like India requires energy resources which are pollution free, reliable, efficient and durable. Solar, wind and hydro power etc. are few of the promising solutions for sustainable development.

1.4 GRID INTEGRATION OF SOLAR PHOTOVOLTAIC SYSTEM

Grid integration of SPV systems has gained importance nowadays because it reduces the use of the conventional sources of energy. A PV system utilizes the energy of the sun, converts it into dc power and then ultimately to ac power using the power electronic devices. The solar power generated from the PV array is supplied to the load and the excess power is supplied to the grid. PV panels generate DC current with the help of sunlight energy using the Photovoltaic effect. The amount of power generated depends upon the irradiance or the amount of sunlight falling on the panels at any given point of time and the location. The DC power generated by the PV array is maintained at its maximum power point using the MPPT technique. The MPPT technique generates the switching pulses which are used for the control of the Boost converter. A DC link capacitor is used in between the Boost converter and the Inverter. The DC- link voltage is maintained at a constant level with the help of inverter control. The output of the inverter is supplied to the load.

The role of inverters used in solar systems is to supply constant voltage and the frequency, even when the load conditions are varying. They are also required to supply the reactive power in case of reactive loads.

The efficiency of the PV systems greatly depends upon the quality and type of PV panels, DC-DC boost converters, Inverters etc. and their interconnections.

1.5 CHALLENGES IN GRID CONNECTED SPV SYSTEMS

Power quality (PQ) usually defines the quality of power at the different levels which includes the generation, transmission and the distribution levels. It is a major concern at the distribution level because it degrades severely at this level of utilization and there are several devices which are very sensitive towards small fluctuations in the power supply. It can be defined in terms of the condition of voltage, current and the frequency. The reason for the degradation of power quality ranges from failure of various equipments, lightening, circuit boards failure, data errors, automatic resets, severe environmental conditions, voltage distortions, nonlinear loads (which draw non- sinusoidal currents) etc.

1.5.1 PROBLEMS RELATED TO POWER QUALITY

A particular range of voltage supply parameters, current and frequency is required for the devices to work properly and the variation in these causes the power quality problems and these need to be properly handled in order to avoid the failure of our equipments and devices.

At point of common coupling (PCC), the power quality issues occur due to the voltage surges, voltage sag, voltage dip, voltage fluctuations, unbalance in the voltage, etc. All these (PQ) problems are mainly due to switching of different types of loads and components in distribution systems. These are the problems related to the system voltage.

The problems related to the current include current harmonics, unbalanced currents, low power factor. These PQ issues related to the current have serious impacts on the electrical system. These can cause an increase in the losses in the electrical components, increased vibrations and noise in the operation of induction motors, heating of electrical wires and cables etc.

1.5.2 CLASSIFICATION OF POWER QUALITY ISSUES

The power quality (PQ) issues can be classified on different basis:

a) **On the basis of events:** This category of the power quality problems are of:
   i) Transient nature: It includes voltage sag or swell, voltage fluctuations, power frequency variations etc.
   ii) Steady State: It includes unbalanced voltages, unbalanced load currents, voltage variations for long durations, poor power factor, etc.

b) **On the basis of quantity:** Under this category, the power quality problems are classified as:
   i) Voltage related problems, which include voltage sag, voltage swell, voltage distortions, under voltage, over voltage, voltage flicker etc.
   ii) Current related problems, which include harmonic currents, unbalanced currents, reactive power component of current etc.
   iii) Frequency related problems, which include frequency variations etc.

c) **On the basis of load or supply system:** Under this category, the power quality related problems can be classified as:
   i) Problems due to load, which include harmonic currents, unbalanced currents, reactive power component of current etc.
   ii) Problems due to supply system, which include voltage distortion, voltage sag, voltage swell, voltage flicker etc.

The degradation of power quality may result in equipment failure, increased vibrations, noise, various losses in wires and cables etc.

1.5.3 COMMON POWER QUALITY PROBLEMS AND THEIR CAUSES

Some of the power quality problems are listed below:

1) Voltage Sag:
   Voltage sag can be defined as the decrease in the normal voltage level between 10% and 90% for a duration of up to 1 minute. Voltage sags are generally caused by the faults on the transmission or distribution levels like connection of heavy loads or starting of large motors etc. Voltage sag may result in malfunctioning of the various equipments such as PLCs, ASDs etc., tripping of the relays, reduced efficiency of rotating machines etc.
2) Very short interruptions:
   This includes the interruption in the power supply for a duration ranging from a few milliseconds to a few seconds. The main reason behind the occurrence of these faults is opening and closing of the devices used for the protection. The tripping of these protection devices may result in the loss of data, improper functioning of devices such as PLCs, ASDs etc.
3) Long interruptions:
   This includes the interruption in the power supply for more than one or two seconds. These are caused due to the failure of equipments due to extreme environmental

conditions such as storms, falling of trees on the electrical lines or poles, failure of protection devices etc.

4) Voltage spike:
   Voltage spike refers to a sudden variation of voltage ranging from several microseconds to a few milliseconds. These may be caused due to lightening, disconnection of heavy loads etc. and may result in the damage of electrical components and insulations, data errors, etc.
5) Voltage swell:
   Voltage swell refers to the sudden increase in voltage for more than one cycle and for less than a few seconds. It may be caused due to starting or stopping of heavy loads, improper load regulation etc. It may result in the loss of data, damage of sensitive equipments, etc.
6) Harmonic distortion:
   This is a condition in which the voltage and current waveforms may take up a non-sinusoidal shape including various harmonics. These may result in overheating of equipments, reduced efficiency of electrical machines, electromagnetic interference present in communication systems, etc.
7) Voltage fluctuations:
   It may refer to the oscillation of voltage, which is amplitude modulated with a signal having a frequency ranging from 0 to 30Hz. This may be caused due to the frequent starting or stopping of electric motors, oscillating loads etc. This may result in the flickering of lights and screens, etc.
8) Noise:
   This may occur due to the superimposition of the power signal with some high frequency signal. This may be caused by the electromagnetic interference, improper grounding, etc.
9) Voltage unbalance:
   It defines the variation of three phase system voltage from the proper balanced condition i.e. having equal angles between the phases and equal magnitude of the three phases. This may be caused due to large single phase loads, improper distribution of the single phase loads to the three phases etc. and it may lead to the presence of negative sequence currents which are harmful for the three phase loads.

1.5.4 METHODS TO IMPROVE POWER QUALITY

Voltage unbalance is a very common problem faced by the three phase systems as most of the loads connected to a distribution system are single phase loads. Also, the non- linear loads connected to the power system can lead to the presence of harmonics, flickering etc. All these issues require some sort of corrective measures. These may include active as well as passive compensators.

i) PASSIVE COMPENSATION

Passive devices mainly consist of capacitors and inductors. They may or may not contain switching devices. Their main aim is to provide reactive power compensation to improve the voltage profile of the system and providing power factor correction. Passive compensators can be divided based on two types of classifications:

a) Classification based on topology:

On the basis of topology, passive filters can be classified as series compensators, shunt compensators or hybrid compensators. Passive series compensators are used to improve power transfer capability in the case of transmission systems, for increasing the stability and improving voltage profile in case of self excited induction generators etc. Although they provide these advantages but they may lead to series resonance.

Passive shunt compensators are mainly used on the load side to provide current compensation, provide power factor correction, voltage regulation and load balancing etc.

b) Classification based on the type of supply system:

On the basis of supply system passive compensators can be classified as single- phase two- wire compensators, three- phase three- wire compensators and three- phase four-wire compensators.

ii) ACTIVE COMPENSATION

a) Active shunt compensation:

It is a method to eliminate present day power quality issues related to the current such as poor voltage regulation, low power factor, unbalanced currents etc.
Among the various methods such as unified power quality conditioners (UPQCs), dynamic voltage restorer (DVR) and custom power devices (CPDs) such as distribution static compensator (DSTATCOM) etc. which can be used to remove the power quality problems the ones which are very frequently used are CPDs and DTATCOMs.

a.1) Distribution Static Compensator (DSTATCOM):

Various loads and equipments connected at the distribution levels are affected by the different power quality issues such as voltage sag, voltage swell, harmonics, etc. A power system is said to be well designed if it operates at the voltage levels which are under acceptable levels. All the electrical equipments are designed to operate under a particular rated voltage or the acceptable variation can be within 5% range. If the variation is more than this, the equipment may malfunction or sometimes it may completely damage.

DSTATCOM is a device generally used for mitigating the current related problems which degrade the power quality like low power factor, unbalanced currents, poor voltage regulation etc. On the basis of the requirement of the system, the designing and configuration of DSTATCOM is done. The main function of the DSTATCOM is to ensure balanced sinusoidal source currents by maintaining DC bus voltage of the VSC at a constant level.

a.1.1) Operation Of DSTATCOM:

Fig. 1.4 shows a 3- phase distribution static compensator, which eliminates harmonics, provide reactive power compensation and load balancing etc.

A DSTATCOM used in the system is of 3-phase 3-wire type. A DC link capacitor is used along with six IGBTs switches to form the DSTATCOM. A control algorithm is implemented which generates the reference current waveforms. These reference current waveforms along with the measured current waveforms are used to generate switching gate pulses using hysteresis current control. This control method is known as the indirect current control method of DSTATCOM.

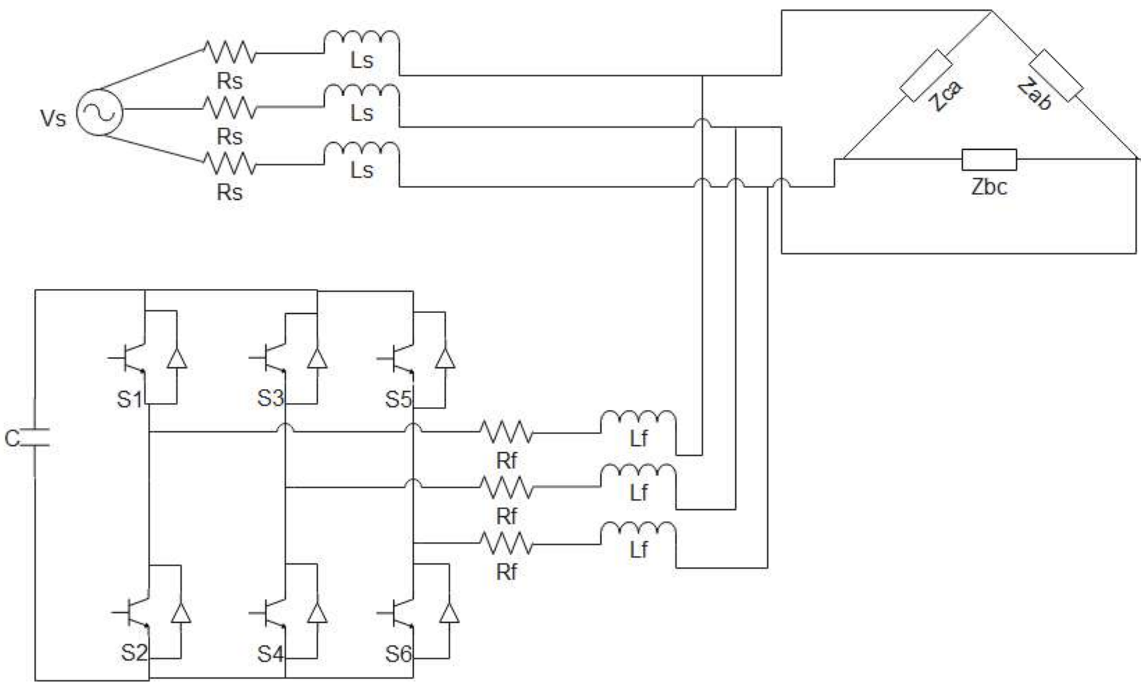

Fig.1.4 A schematic diagram of a 3-phase 3-wire distribution static compensator (DSTATCOM)

a.2) Unified Power Quality Compensators (UPQC):

UPQC refers to a combination of both shunt and series compensators. It can be used for the systems having voltage as well as current based problems. It consists of two voltage source converters (VSCs) connected together with the help of a DC link capacitor or two current source converters (CSCs) connected together with the help of an inductor at DC bus.

The shunt component of the UPQC is called distribution static compensator (DSTATCOM) and the series component is known as dynamic voltage restorer (DVR). DSTATCOM part of the UPQC takes care of the reactive power compensation, load balancing, harmonic elimination etc. whereas the DVR part of the UPQC takes care of the voltage sag, voltage swell, fluctuations, spikes, voltage unbalance etc. by injecting the voltage between the supply and load and maintaining the voltage of the load at its reference value (say 800V).

UPQC can be classified on the basis of:

- Supply:

On the basis of supply, UPQC can be divided into two- wire UPQC, three- wire UPQC and four- wire UPQC.

- Converter:

On the basis of converter, UPQC can be divided into Voltage Source Converter based UPQC and Current Source Converter based UPQC.

- Topology:

On the basis of topology, UPQC can be divided into right- shunt UPQC and left- shunt UPQC.

- Method of control:

On the basis of method of control, UPQC can be divided into UPQC- P, UPQC- Q and UPQC- S etc.

b) Active series compensation:

It is a method to eliminate voltage based power quality problems such as voltage sag, voltage swell, flicker, spikes, voltage imbalance, distortions etc. These compensators are used to protect the loads from quality problems related to the voltage by injecting the voltage of required magnitude and frequency. These are also called dynamic voltage restorers (DVRs) and solid- state synchronous series compensators (SSCs).

Active series compensators can be classified as:

- Type of power converter:

On the basis of power converter, active series compensators can be divided into Voltage Source Converter (VSC) and Current Source Converter (CSC).

- Topology:

On the basis of topology, active series compensators can be divided into half- bridge voltage source converter, full- bridge voltage source converter etc.

- Number of phases:

On the basis of number of phases, active series compensators can be divided into single-phase two- wire systems, three- phase three- wire systems and three- phase four- wire systems.

b.1) Static Synchronous Compensator (STATCOM or SSC):

A STATCOM consists of a high power switching device, solid state elements and some auxiliary devices. It uses force commutated devices such as IGBT, GTO etc. for the purpose of controlling the reactive power and hence improves the stability of the system. It can either generate or absorb the reactive power depending upon the stability of the system.

Different standards are adopted by various industries and organizations which make sure that the acceptable level of power quality is maintained.

Various IEEE standards related to power quality are:

• IEEE standard 519: for harmonic control

Tables 1.2- 1.5 show the limits on currents and voltages that one needs to follow while designing a system.

TABLE 1.2 IEEE STANDARD 519-2014: VOLTAGE DISTORTION LIMITS

Bus voltage at PCC	Individual harmonic (%)	Total harmonic distortion (THD%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High voltage systems can have upto 2.0% THD where the cause is an HVDC terminal

TABLE 1.3 CURRENT DISTORTION LIMITS FOR SYSTEMS RATED 120V THROUGH 69 KV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.
[b]Current distortions that result in dc offset, e.g., half wave converters are not allowed.
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/IL.
where
I_{SC} = maximum short- circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at PCC under nomal load operating conditions

TABLE 1.4 CURRENT DISTORTION LIMITS FOR SYSTEMS RATED ABOVE 69KV THROUGH 161KV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0

50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.
[b]Current distortions that result in a dc offset, e.g., half- wave converters are not allowed.
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.
where
I_{SC} = maximum short- circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

TABLE 1.5 CURRENT DISTORTION LIMITS FOR SYSTEMS RATED > 161 KV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{SC}/I_L	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
< 25[c]	1.0	0.5	0.38	0.15	0.1	1.5
25 < 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

[a]Even harmonics are limited to 25% of the odd harmonic limits above.
[b]Current distortions that result in a dc offset, e.g., half- wave converters are not allowed.
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.
where
I_{SC} = maximum short- circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

• IEEE standard 1159: for monitoring electric power quality:

TABLE 1.6 CATEGORIES AND TYPICAL CHARACTERISTICS OF POWER SYSTEM ELECTROMAGNETIC PHENOMENON

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 µs rise	50 ns – 1 ms	
1.1.3 Millisecond	> 1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3- 50 ms	0-4 pu[a]
1.2.2 Medium frequency	5- 500 kHz	20µs	0-8 pu
1.2.3 High frequency	0.5- 5 MHz	5 µs	0-4 pu
2.0 Short- duration root- mean- square (rms) variations			
2.1 Instantaneous			
2.1.1 Sag		0.5- 30 cycles	0.1-0.9 pu
2.1.2 Swell		0.5- 30 cycles	1.1-1.8 pu
2.2 Momentary			

2.2.1 Interruption		0.5 cycles- 3s	<0.1 pu
2.2.2 Sag		30 cycles- 3s	0.1-0.9 pu
2.2.3 Swell		30 cycles- 3s	1.1-1.4 pu
2.2.4 Voltage Imbalance		30 cycles- 3s	2%-15%
2.3 Temporary			
2.3.1 Interruption		> 3s- 1min	<0.1 pu
2.3.2 Sag		> 3s- 1min	0.1-0.9 pu
2.3.3 Swell		>3s- 1min	1.1-1.2 pu
2.3.4 Voltage Imbalance		>3s- 1min	2%-15%
0 Long duration rms variations			
0.1 Interruption, sustained		> 1min	0.0 pu
0.2 Undervoltages		> 1min	0.8-0.9 pu
0.3 Overvoltages		> 1min	1.1-1.2 pu
0.4 Current overload		> 1min	
1 Imbalance			
1.1 Voltage		Steady state	0.5-5%
1.2 Current		Steady state	1.0-3.0%
2 Waveform distortion			
2.1 DC offset		Steady state	0-0.1%
2.2 Harmonics	0-9 kHz	Steady state	0-20%
2.3 Interharmonics	0-9 kHz	Steady state	0-2%
2.4 Notching		Steady state	
2.5 Noise	Broadband	Steady state	0-1%
3 Voltage fluctuations	< 25 Hz	Intermittent	0.1-7% 0.2-2P_{st}
4 Power frequency variations		< 10s	±0.10Hz
NOTE—These terms and categories apply to power quality measurements and are not to be confused with similar terms defined in IEEE std 1366™- 2012 and other reliability- related standards, recommended practices, and guides.			

[a]The quantity *pu* refers to *per unit*, which is dimensionless. The quantity 1.0pu corresponds to 100%. The nominal condition is often considered to be 1.0pu. In this table, the nominal peak value is used as the base for transients and the nominal rms value is used as the base for rms variations.

[b]Flicker severity index P_{st}as defined in IEC 61000-4-15:2010 and IEEE std 1453™.

Various techniques are developed in order to minimize the problems related to the power quality and in a way enhance the quality of power of the system. If the system consists of non linear loads, then the measures which can be taken include the use of various power filters which include active filters, passive filters, shunt filters, series filters, or a combination of shunt and series filters.

1.6 OUTLINE OF THE DISSERTATION

This dissertation has been divided into 5 chapters which are as follows:

1) Chapter 1 gives a brief introduction about the solar potential in India and the generation of the solar power, power quality issues and their mitigation using DSTATCOM.
2) Chapter 2 presents the literature review on grid connected SPV systems.

3) Chapter 3 describes the photovoltaic generating systems, various topologies of the grid connected PV systems, various components of the PV system, MPPT, and the control techniques of 3- phase VSI
4) Chapter 4 presents the mathematical modeling of the PV cell, module and array, and their P-V and I-V characteristics. It also contains the simulink models of grid connected PV systems.
5) Chapter 5 contains the conclusion and future scope of work related to the area of SPV systems with grid integration.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

A grid connected PV system requires a complete knowledge about all the issues and challenges while connecting PV system to the grid along with the control of our PV system. A brief literature review on designing of the complete PV system along with the MPPT techniques and the inverter control technique have been presented in this chapter.

2.2 LITERATURE REVIEW

With the growing population, the energy requirements are increasing at a fast pace and to meet these energy requirements is one of the biggest challenges of the present time. Various other challenges like global warming and the cost of the energy has made us think about the alternative clean sources of producing the power. Various countries like USA, China, Germany, and Sweden have already increased their renewable energy production by improving the policies and framing the deadlines to accomplish the predefined targets. India has also set its target of 175 GW of solar production to be accomplished by 2022 and states such as Karnataka, Gujarat and Tamil Nadu have quickly adopted the different policies to reach the defined target[1]. The total installed capacity(in MW) of power stations are mentioned in[2].

The developing countries face a problem of less amount of energy production and therefore less amount of energy that reaches the people. The renewable energy sector which includes wind energy, solar energy, geothermal energy, tidal energy, ocean energy, biomass energy, etc. has large potential to meet storage of electricity and energy requirements [3-4].

Recently, huge investment has been made in the solar energy sector and this energy is easily available for the industrial as well as domestic use. The investment in the solar energy sector faces a lot of challenges such as land scarcity, slow progress, etc. but with proper execution and financing these challenges can be overcome [5].

2.2.1 SOLAR: A SOURCE OF CLEAN ENERGY

Approximately 75% of the total CO_2 emission in the world comes from the energy sector and this can be reduced by utilizing the alternate sources of energy which mainly includes the renewable sources of energy. The net energy ratio is defined as:

$$NER = \frac{Energy\ output\ of\ the\ system}{Non-renewable\ energy\ input} \tag{2.1}$$

and the value of NER should be more than one for renewable energy systems and for the non-renewable systems this value is less than one[6].

Several air pollutants such as NO_X, SO_2, PM, and O_3 cause a significant amount of damage cost. This damage cost is related to the problems which are caused to the general public during the process of electricity generation. This cost is more in the case of fossil fuels as compared to the renewable sources of energy. An Impact Pathway Analysis (IPA) is done which includes emission i.e. taking into account all the pollutants produced such as NO_X, etc. , dispersion i.e. calculation of the amount of the pollutants dispersing into the atmosphere, impact i.e. calculation of the damage caused to the people or the atmosphere and the cost i.e. monetary valuation of these impacts[7]. This evaluation shows that the renewable sources of energy produce a minimal damage cost and the increased production of energy from these sources of energy can lead to the sustainable development.

To reduce our dependency on the fossil fuels, renewable sources of energy are far better solutions to the increased generation of the amount of pollutants. Solar rooftop PV generation can successfully meet the demands of a number of people along with revenue generation. Many countries are using these rooftop systems now to meet their energy requirements. In Germany, out of the total of 40GW PV generation, 74% generation is from the rooftop systems and out of this, 70% generation is for the residential purpose. Despite of all the advantages the rooftop systems offer, there are a lot of barriers which come in the way of rooftop solar power generation which include lack of awareness related to the technology, low transparency in implementation of policies, less number of financial supports and the lack of skilled manpower. All these barriers need to be removed in order to reduce our dependency on the conventional sources of energy and head towards the clean source of energy[8].

The sustainable energy goals are presented in [9] which are required to be considered such as low poverty, no hunger, good health, quality education, affordable energy, clean energy, responsible consumption and production etc.

2.2.2 SPV ARRAY CHARACTERISTICS & EFFECT OF ENVIRONMENTAL FACTOR

As India is located near to the equator, so solar power is a great source of electricity generation. A “Solar agri- electric model” is presented in [10] according to which people are now using the land under the solar panels for the agricultural practices which results in improved soil quality as well as water retention.

When installing a PV system, a proper tilt determines an increase in the total energy or the radiation collected by the solar panels which result in increased generation of electricity. The tilt angles adjusted four times a year gives the optimized production [11].

The PV module output is affected by the environmental conditions and the module operating temperature depends upon different factors which include ambient temperature, irradiance, wind speed, wind direction etc. [12].

2.2.3 MODELING &ANALYSIS OF SOLAR PV ARRAYS

The mathematical modeling of a PV cell is presented [13] and the simulation results based on the I-V and P-V characteristics under varying irradiance and varying temperature are presented. Modeling and simulation of a PV module [14-17] and an equivalent model of PV array is developed and the output characteristics of the PV array are shown [18-22]. A Xilinx System Generator (XSG) based modeling of PV system is shown in [23]

The PV cells are of different types, such as monocrystalline, polycrystalline and thin-film solar cells etc. Mathematical modeling of a polycrystalline PV cell has been presented in [24], and the effect of varying weather and loading conditions is studied.

2.2.4 TOPOLOGY IN GRID INTEGRATION OF SPV

There are different topologies for connection of the PV systems to grid, and these can be categorized into[25]:

i) Centralized topology
ii) Master- slave topology
iii) String topology
iv) Team concept topology
v) Multi- string topology
vi) Modular topology

The output of a PV system vary and it is maximum at the knee of its I-V curve, this point is known as the Maximum Power Point (MPP) of the PV array and it is necessary to operate the PV system at this point to extract PV array maximum power at all times. The Perturb and Observe (P&O) technique of Maximum Power Point Tracking (MPPT) is studied in [26-35] and Incremental conductance based MPPT technique is presented in [32-36]. An FPGA based implementation of P & O MPPT is shown in [37-38].

The MPPT technique generate switching pulses which are used to control the ON/OFF switching of the MOSFET used in the Boost converter. The designing of the Boost converter is studied in [39-40].

The DC voltage received from the Boost converter is then converted to an AC voltage for grid connection. This is done using an inverter, which transforms the DC voltage into an AC voltage, which is then synchronized with the grid voltage & frequency at point of common coupling (PCC). During the day time this PV system supplies the power to the grid as well as the load along with improving the power quality and during night it does not supply any power and only works as a DSTATCOM for improving the power quality. Power quality is a very important matter of concern when installing a grid connected PV system. The various disturbances caused in the system can severely harm the equipments connected to it. There are different sources of these disturbances which are clearly highlighted in [41]. The power quality issues [42] and their mitigation techniques are explained in [43].

The inverters used for the grid interconnection are Voltage Source Inverters (VSI) and the control techniques used for these VSIs are of two types: Voltage Control of VSI and Current control of VSI. A VSI is generally expected to perform following functions in a Distributed Generation Systems [44]:

i) Load voltage stabilization

ii) Uninterruptable power supply
iii) Reactive power support
iv) Active power support

With the current control of the VSI, it is possible to operate the entre range of load at the unity power factor (UPF). So for the applications where mainly require reactive power support or active power filtering is needed, current control of VSI is a better option. One of the control techniques used for the grid connected VSIs is Power Balance Theory (PBT) which is explained in [45-46] for two applications:

1) Unity Power Factor
2) Voltage regulation

The various grid synchronization techniques such as Synchronous Reference Frame based Phase locked loop (SRF-PLL), multiple reference frame based PLL (MRF-PLL), dual second order generalized integrator based PLL (DSOGI-PLL) etc. are elaborated in [47]. Various other control techniques used for the grid connected inverter control, include Adaptive technique[48], cross-coupling and decoupling techniques[49], Instantaneous Reactive Power Theory - based control [50-51], Synchronous Reference Frame based inverter control [52] etc.

These control techniques are developed keeping in mind the effect they are going to create over the power quality of the system.

2.3 CONCLUSION

This chapter describes the literature review in solar PV technology, issues & challenges in grid connected solar system, the power quality problems and challenges in installation of SPV array and implementation of the different MPPT algorithms and the various control techniques of the grid connected inverters etc.

CHAPTER 3

MATHEMATICAL MODELING & ANALYSIS OF PHOTOVOLTAIC POWER GENERATION SYSTEMS

3.1 INTRODUCTION

Photovoltaic is a combination of two words, photo and voltaic, where photo stands for light and voltaic is referred to the production of electricity. So, Photovoltaic technology refers to the generation of electricity from light.

The development of solar technology began in 1839 with the research of French scientist Alexander Edmond Becquerel (1820-1891). While experimenting with a solid electrode in an electrolytic solution he discovered that a voltage was developed when the light struck the electrode. This is the basic principle behind the conversion of light or the solar irradiation into electricity and is known as photovoltaic effect. Photovoltaic effect was discovered way before the discovery of the Photoelectric effect. In both of these effects the absorption of photons takes place, but in Photoelectric effect, the electrons are ejected into the space, whereas in Photovoltaic effect, these electrons are raised to a higher energy level in the same material.

The solar Photovoltaic technology is considered to be a clean technology as it does not release any harmful gases during its operation so it does not pollute the environment. This is the main reason behind the increased use of these systems.

3.2 PV ENERGY CONVERSION

Solar energy reaches the earth in the form of electromagnetic waves (or irradiation). These electromagnetic radiations are made up of small energy particles called photons. From the equation,

$$E = h\nu \qquad (3.1)$$

where, h = Plank's constant,

ν = frequency of photon

it is observed that the energy of the photon is inversely proportional to its wavelength.

When the semiconductors are exposed to light, the photons with a certain energy band gets absorbed, the remaining photons either pass through the material or gets reflected without being absorbed. When the photons get absorbed, the energy is transferred to the electron of that semiconductor.

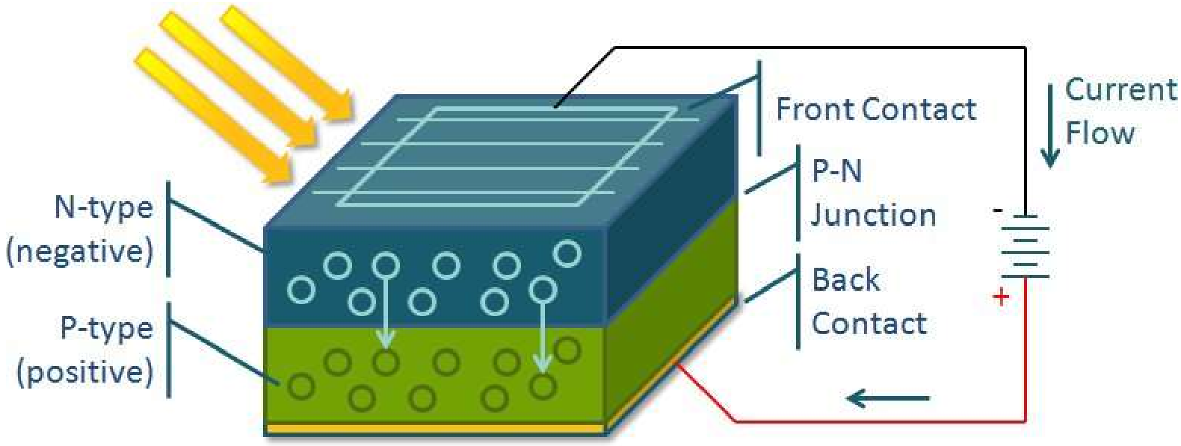

Fig. 3.1 A PV cell energy conversion

3.2.1 PV CELL

In 1954, Bell Telephone Laboratories in Murray Hill, N.J. unveiled the first practical solar cell with a slightly modified wafer of silicon with an efficiency of 6 percent.

The conversion of sunlight into electrical energy is a single step process. No moving parts or chemical reactions are associated with this conversion process.

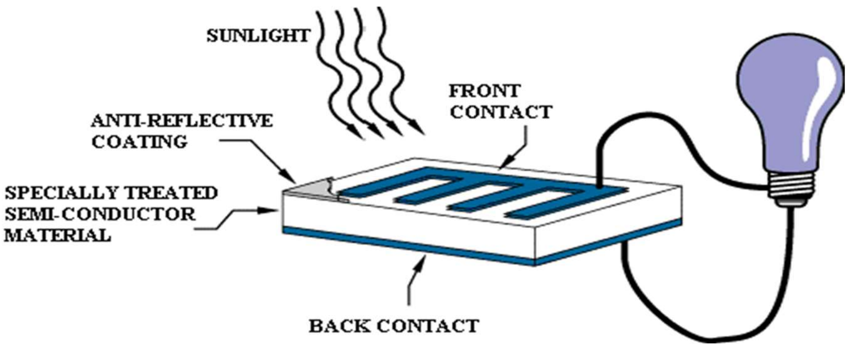

Fig.3.2 A PV cell

A PV or a solar cell forms a junction in the presence of illumination. Visible photons have the energy sufficient to excite the electrons present in the atoms of PV cells from valence band to the conduction band. Electron–hole pairs are generated on both sides of the junction i.e. the p-type base and the n-type emitter. A potential difference or an electromotive force is generated between the terminals of the cell by the excited electrons. The photovoltaic device is designed such that the excited electrons are pulled out to feed the external circuit.

A bypass diode is generally used on every cell of the module which prevents the cell from becoming reverse biased but as this is not economically feasible, so a bypass diode is used across each module.

Manufacturing of PV cells can be done using two types of materials i.e. a semiconductor material that converts the absorbed light energy into electron-hole pairs or a semi-conductor material having a junction that separates photo-generated carriers into electrons and holes.

Different types of PV cell technologies are shown in the Fig. 3.3

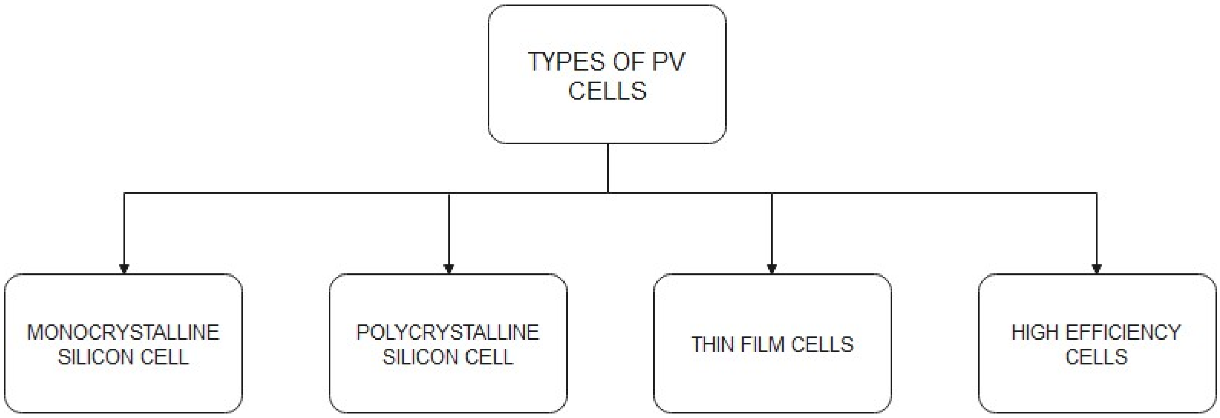

Fig.3.3 Different types of PV cells

• MONOCRYSTALLINE SILICON CELL: Just like the name suggests, a monocrystalline solar cell is made from a single crystal of silicon. Silicon is formed into bars and cut in the form of wafers in order to make a monocrystalline solar cell. Their efficiency is around 15-24%.

• POLYCRYSTALLINE SILICON CELL: They are also made up of silicon but instead of using a single crystal, many fragments of silicon are melted together and formed into wafers. They are also known as multi- crystalline silicon cells. They have an efficiency of about 12-14% and are relatively cheaper than the Monocrystalline silicon cells.

• THIN FILM CELLS: Thin film solar cells consist of thin homogenous layers of silicon. They can be used in the place of normal brick tiles in a solar roof which serves as an advantage in spite of their lower efficiency of 6%.

• HIGH EFFICIENCY SOLAR CELLS: these cells have three junctions. The upper substrate forms two junctions and is made up of high solar energy absorbing materials from III-V semiconductor family whereas the lower substrate is made up of a silicon wafer. A layer of selenium is applied between the two wafers. They have a high efficiency of about 40% but this technology is still under development phase.

3.2.2 PV MODULE

A single PV cell is incapable of providing sufficient output, so it is required that these cells are connected together to provide a required standard output voltage and power. A number of photovoltaic cells are grouped together and are generally connected in series to form a photovoltaic module. Table 3.1 shows the electrical characteristics of a typical 305W peak power rating module.

TABLE 3.1 ELECTRICAL CHARACTERISTICS OF SUNPOWER SPR-305-WHT PV MODULE

NAME	SunPower SPR-305-WHT
Rated Power (P_{mp})	305W
Voltage obtained at maximum power(V_{mp})	54.7V
Current obtained at maximum power(I_{mp})	5.58A
Open circuit voltage(V_{oc})	64.2V
Short circuit current(I_{sc})	5.96A
Total number of cells connected in series(n_S)	96
Total number of cells connected in parallel(n_P)	1

3.2.3 PV ARRAY

The output of a solar module depends upon the ambient temperature and the intensity of light, so the rating of a module must be specified under such conditions. The rating of a PV module is generally considered at a standard temperature of 25°C and standard irradiation of 1000 W/m^2 and these are known as standard test conditions.

The modules are connected in series or parallel or the combination of both in order to obtain the desired output voltage and power, which can be used in our PV generating systems.

A shunt resistance is mainly present due to the presence of some manufacturing defects.

The slope of the I-V curve determines the approximate shunt resistance (R_{SH}), which determines the available parallel current paths, which ultimately limits the output current of the cell. The modules, which are physically damaged, sometimes show a reduced value of shunt resistance as new parallel current paths are formed because of this damage. Fig. shows I-V characteristics of a PV cell.

The slope of I-V curve near the open circuit point i.e. the V_{OC}, determines the series resistance of the cell, which gives the resistive losses in the cell.

3.3 TOPOLOGIES OF GRID CONNECTED PV SYSTEM

Grid tied SPV systems can have various topologies depending upon the requirements. Fig. shows classification of PV modules. These can be classified as:

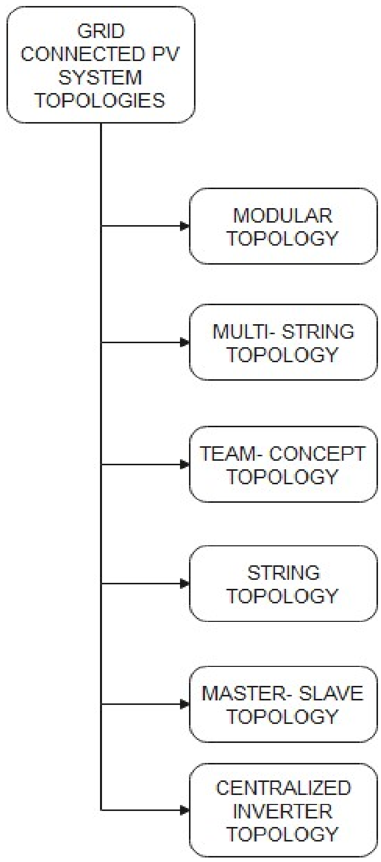

Fig.3.4 Flowchart showing grid connected PV system topologies

3.3.1) Modular topology: For the PV systems with low power generation (< 500W) modular topology can be used. In this topology an inverter is connected to each module. It provides better monitoring of the modules and losses which occur due to partial shading are also low.

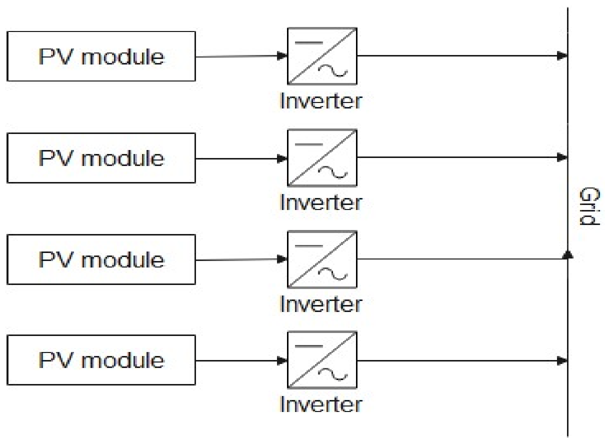

Fig.3.5 Modular topology

3.3.2) Multi- string topology: This topology consists of a single inverter tied to the entire SPV system. DC to DC converters are connected at the end of each PV string and the inverter is connected to these DC to DC converters. Due to the presence of DC to DC converters, losses are increased in the system but the cost is relatively low due to the presence of a single inverter.

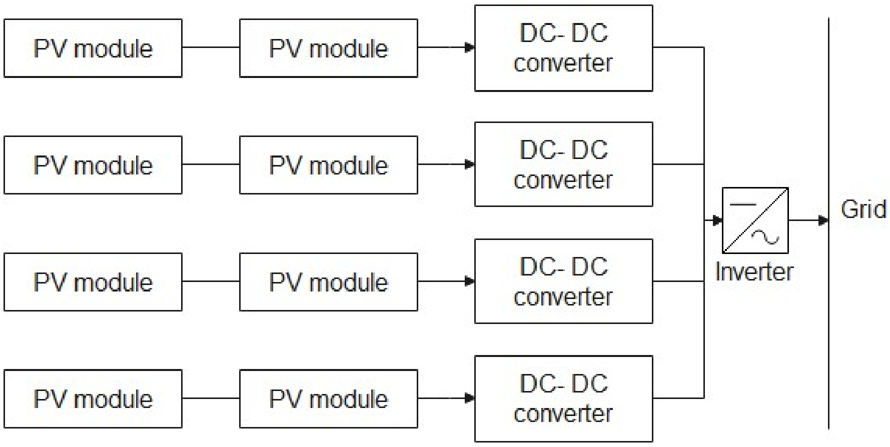

Fig.3.6 Multi- string topology

3.3.3) Team concept: This topology is used in the PV systems generating large amount of power. When the irradiance is low one inverter is connected to all the PV arrays, but as the irradiance increases, strings of PV arrays are formed and are connected to individual inverters which then operate at their rated power.

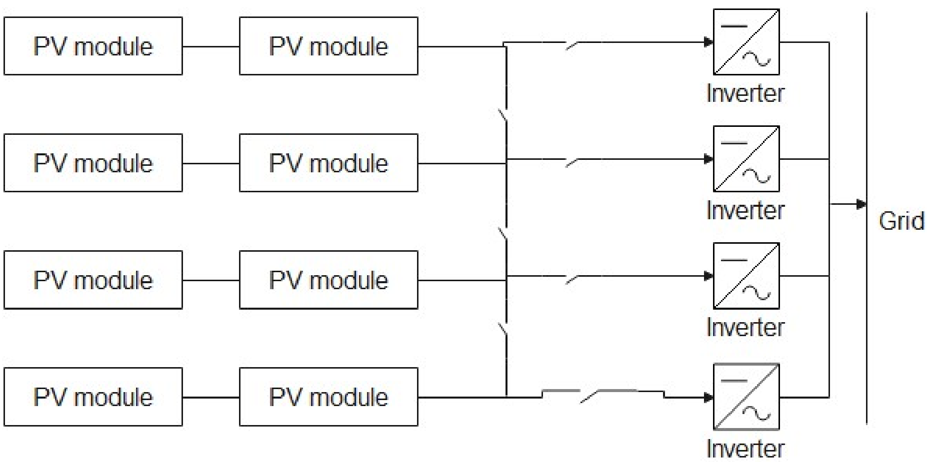

Fig.3.7 Team- concept topology

3.3.4) String topology: In this topology, all the string are connected to an individual inverter. The size of the system can be easily increased in this topology as the addition of new strings is very easily possible in the system. Its cost is high because of the presence of inverter at the end of each string of PV modules.

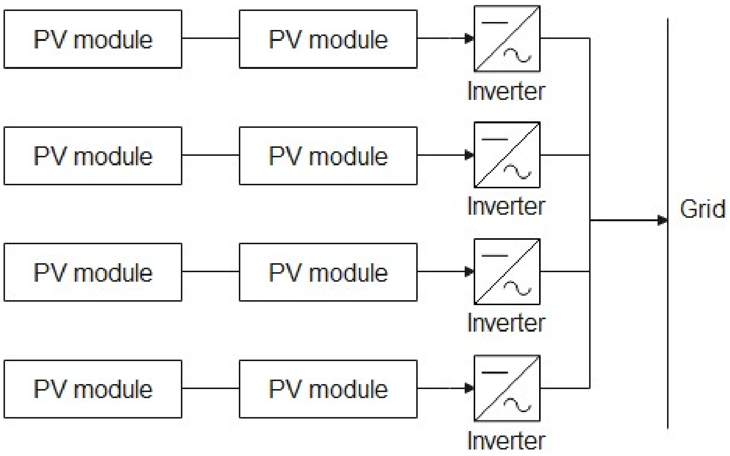

Fig.3.8 String topology

3.3.5) Master- slave topology: Many inverters are connected in parallel in this topology and only the required number of inverters is used at a time. When the irradiance is low, only a few inverters are operational and the others are shut down. This increases the efficiency of the operation and the reliability of the system is improved.

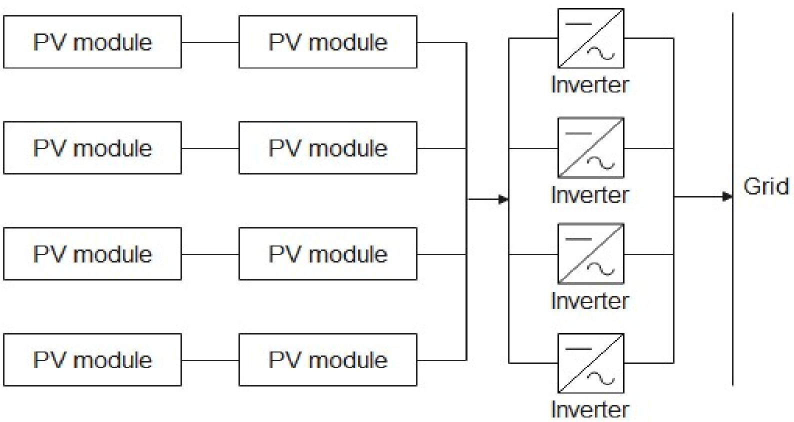

Fig. 3.9 Master- slave topology

3.3.6) Centralized inverter topology: This topology is used in the PV systems generating power in megawatts range. The entire PV array is connected to a single inverter so the reliability is low in this type of topology. The system cost is low because of the presence of a single inverter.

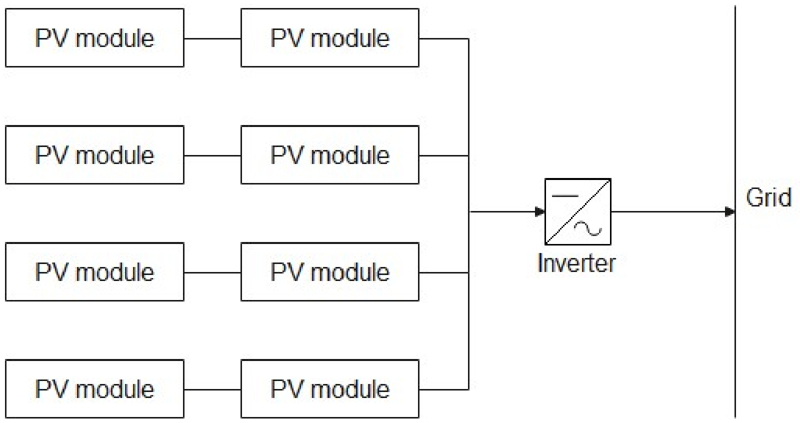

Fig.3.10 Centralized inverter topology of grid connected PV system

3.4 FACTORS THAT NEED TO BE CONSIDERED BEFORE INSTALLING A PV SYSTEM

A proper planning and designing need to be done before installing a PV system. Some of the factors which need to be considered are:

3.4.1 What is the purpose of installing the system?:

PV installation is done for a number of reasons such as:

i) For meeting our household electricity requirements: this system is generally considered to be less than 5MW. The size of the generation depends upon the individual household requirements.

ii) For the entire building, industry or an organization: these require a medium scale generation of electricity

iii) For supplying electricity to the DISCOMS: these require a generation ranging from a MWs to GWs.

3.4.2 The duration up to which the electricity generation needs to be done:

Large amount of money is needed at the time of PV installation. So we need to determine whether the generation needs to be done for the time more than the time required to recover that cost of installation along with fetching a good amount of profit.

3.4.3 Amount of energy required:

The amount of energy or the electricity required by a particular system depends upon the number of electrical devices that have to be powered using the PV system. A proper calculation is required to be done in order to determine the number of panels required in the system.

3.4.4 Rooftop/ Ground mounted system:

Rooftop systems are generally used when we generate electricity of our household requirements. As these systems are installed on the rooftops, so, these type of systems do not require an additional amount of space for their installation.

Ground mounted systems are generally used when we have a sufficient amount of space for the installation of our system. These systems are generally used for the production of large amount of electricity. Large solar farms are an example of ground mounted systems.

3.4.5 Location:

This is a very important factor that need to be considered before installing the PV system. The PV system is installed in the region where a sufficient amount of sunlight is received during the day time. Also one need to see if it is surrounded by the tall buildings or trees because this may reduce the amount of sunlight falling on our solar panels.

3.4.6 Cost of the system:

Before installing the PV system, one needs to calculate the cost of our system. It is analyzed whether we require Mono-crystalline or poly-crystalline solar panels for the system.

3.5 DC to DC BOOST CONVERTER

Boost converter is a type of DC to DC converter that converts an input voltage to a higher output voltage then compared by the load through switching actions. It plays a crucial role in maximizing efficiency of solar PV modules. A semiconductor switch with either MOSFET or IGBT is used in the Boost converter depending upon the power level.

The main components of a boost converter include:

Inductor (L),
Capacitor (C),
Controlled switch (S),
Diode (D),
Power semiconductor and
Load

The main phenomenon responsible for its working is the exchange of energy between the inductor and capacitor used in designing the boost converter. Fig. 3.11 shows the Boost converter circuit diagram.

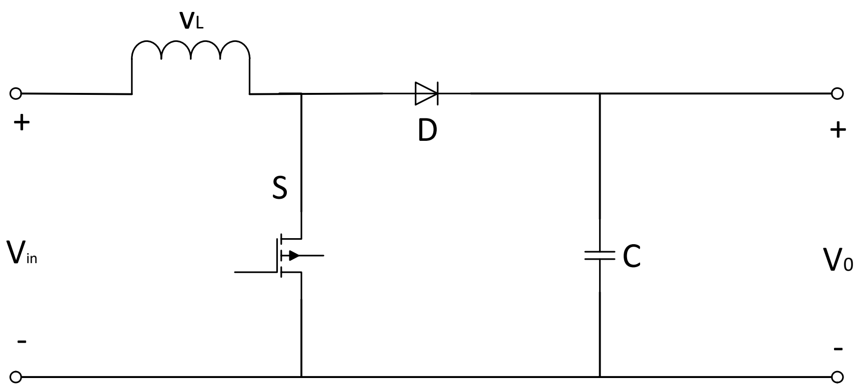

Fig. 3.11 Boost converter circuit diagram

The inductor stores the magnetic energy which is then transferred to the capacitor in the next cycle.

$$\text{Energy stored in inductor} = \frac{1}{2} L . i_L{}^2 \tag{3.2}$$

where, i_L : current through the inductor

$$\text{Energy stored in capacitor} = \frac{1}{2} C . v_0{}^2 \tag{3.3}$$

where, v_o : voltage across the capacitor

The fundamental equations of current and voltage can be expressed as

$$v_L = L\frac{di_L}{dt} \tag{3.4}$$

$$i_c = C\frac{dv_c}{dt} \tag{3.5}$$

The energy stored in the inductor is transferred to the capacitor using the relation between the current and the voltage as given in the equations (3.4) and (3.5).

When the switch is closed (ON), the inductor begins to charge by drawing the energy from the source which is transferred to the capacitor when the switch is open(OFF). On reaching the steady state, voltage output becomes greater than the voltage input and the duty ratio determines the magnitude of the output voltage.

Mode of operation of a Boost converter:

Mode 1: Switch (S) is open

Assuming the steady state operation and inductor being fully charged during the previous cycle of operation, the inductor acts as a current source and current passes through the diode and charges the capacitor. Hence, the voltage across the capacitor increases. Now the inductor voltage is the difference between the input and output voltage.

Mode 2 : Switch (S) is closed

In this stage the diode is reverse-biased by the capacitor voltage, so it will be open circuited. The voltage across the inductor will now be equal to the input voltage. The current through the inductor starts to rise from the initial value and the output voltage will be supplied only by the capacitor.

During the steady state operation, the average voltage of the inductor is zero, so a constant inductor current is obtained.

When we equate the average voltage of inductor equal to zero, i.e. $v_L = 0$, we get

$$\frac{1}{T_S}[V_{in}.DT_S - (V_0 - V_{in})(1-D).T_S] = 0 \quad (3.6)$$

$$V_0 = \frac{V_{in}}{1-D} \quad (3.7)$$

where,

T_S : switching period

$$T_S = \frac{1}{f_s} \quad (3.8)$$

where,

f_s : switching frequency

Also,

$$T_S = T_{on} + T_{off} \quad (3.9)$$

Duty cycle is defined as:

$$D = \frac{T_{on}}{T_S} = \frac{T_{on}}{T_{on}+T_{off}} \quad (3.10)$$

The value of duty cycle lies between 0 to 1, as the output of the converter is always greater than the input voltage i.e.

$$0 \leq D \leq 1$$

For a lossless system,

$$V_{in}I_{in} = V_0 I_0 \quad (3.11)$$

where,

I_{in} : average input current

I_0 : average output current

Now, input current can be given as

$$I_{in} = I_L = \frac{V_0}{V_{in}} I_0 \quad (3.12)$$

$$I_{in} = \frac{I_0}{1-D} \quad (3.13)$$

where,

I_L : average inductor current

Ripple current is the difference between the maximum and the minimum value of inductor current in steady state. Ripple current can be given as

$$\triangle I_L = I_{L_{max}} - I_{L_{min}} = \frac{V_{in}}{L} DT_S \quad (3.14)$$

3.6 MAXIMUM POWER POINT TRACKING

The DC power produced by the PV array is variable and is a function of temperature and the solar irradiance. Hence, it is required to extract the maximum power from the array at any given time under certain conditions. Therefore, maximum power point tracking(MPPT) is required. It is an algorithm that works on the feedback mechanism and locates point present on the trajectory of power obtained from the PV array, where the product of voltage and current is maximum i.e. the power is maximum. The voltage at which the maximum power point is obtained is known as maximum power point voltage or the voltage at peak power. Fig. 3.13 shows the I-V & P-V characteristics of a PV array.

The maximum power point of the PV array can be given as

$$P_{mp} = V_{mp} \times I_{mp} \quad (3.15)$$

where,

V_{mp} : voltage of the PV array at maximum power point

I_{mp} : array current at maximum power point

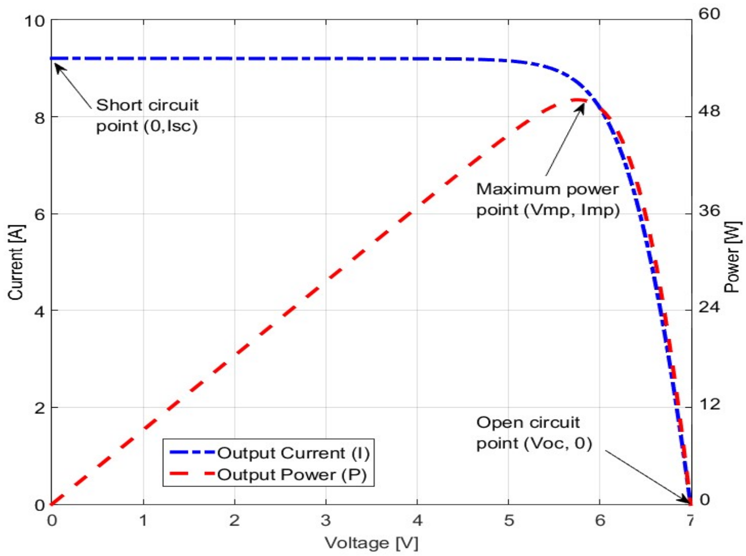

Fig. 3.12 P-V and I-V curves showing MPP of PV module

3.6.1 MPPT TECHNIQUES

MPPT is one of the most cost effective ways to improve the overall PV system performance. In the conventional MPPT techniques, the power at any instant is calculated by measuring the voltage and current obtained from the PV array and accordingly the duty cycle of the boost converter is adjusted to match the maximum power point. The purpose of the various MPPT techniques is to control the duty cycle of the DC to DC converter.

The following MPPT algorithms are frequently used:

(i) Perturb and Observe(P&O)
(ii) Incremental Conductance
(iii) Variable step incremental resistance
(iv) Adaptive fuzzy
(v) Fractional OC method
(vi) Sliding mode control

Among these methods, P&O and Incremental conductance are most widely used methods because they are relatively simple to design and can be easily implemented.

3.6.2 PERTURB AND OBSERVE TECHNIQUE

P&O technique is being used to implement MPPT in solar PV system simulation study in MATLAB/ Simulink. Two major challenges faced by the PV modules are:

a) Low efficiency: The power output generated by the PV modules is generally less than 17%.

b) Intermittency: The changing weather conditions vary the output power produced by the solar Photovoltaic modules. The PV module power output depends upon the irradiance as well as the temperature.

These varying environmental conditions cannot be controlled so, if one wants to maximize the output power generation of the PV modules, they need to be operated at their maximum power point. In this technique, the voltage and current of PV modules is measured & output power is calculated. Fig 3.14 shows a flowchart for implementation of the P&O MPPT method. A small perturbation is given, which causes a variation in the power generated by the PV module. The idea behind this technique is that, at a given point, if the power output increases, then we move in the same direction, otherwise, the perturbation is reversed.

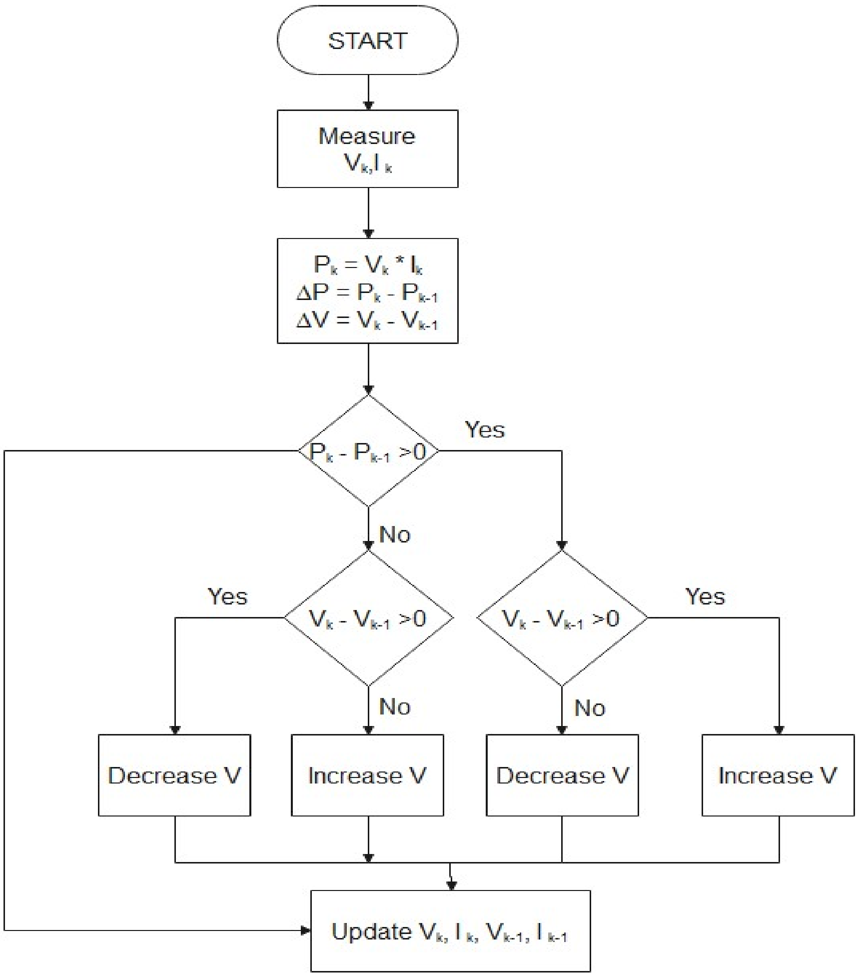

Fig.3.13 Flowchart of perturb and observe MPPT algorithm

There are four cases that occur during implementation of this algorithm:

Case 1: If voltage and power increases ($\Delta V > 0, \Delta P > 0$):

If this is the case, i.e., with the increase in voltage, the power output of the module also increases, it shows that the operating point of PV module is present on the left side of the maximum power point (MPP), so the perturbation is given to make it reach to the right of the maximum power point.

Case 2: If voltage and power decreases ($\Delta V < 0, \Delta P < 0$):

If this is the case, i.e., with the decrease in the module voltage, if the power output of the module also decreases, it implies that the PV module operating point is present at the right side of the MPP, so perturbation is given to make it reach to the left of the maximum power point.

Case 3: If voltage increases and power decreases ($\Delta V > 0, \Delta P < 0$):

If this is the case, i.e., if the power output of the PV module gets decreased on increasing the module voltage, it implies that PV module operating point is at the right side of MPP, so the perturbation is given to make it reach to the left of the maximum power point.

Case 4: If voltage decreases and power increases ($\Delta V < 0, \Delta P > 0$):

In this case, if the power output of the PV module increases with the decrease in the PV module voltage, it indicates that the operating point of the PV module is present at the right side of the MPP, so the perturbation is given such that the operating point shifts to the left and reaches the maximum power point.

In Perturb and Observe technique,

$$\frac{dP}{dV} = 0 \tag{3.16}$$

where,

dP : small change in power output of the PV curve

dV : small change in voltage output of the PV curve

i.e. the derivative will be zero at the maximum point.

3.7 IMPLEMENTATION OF P&O MPPT METHOD USING XILINX FPGA BOARD

FPGA technology is one of the most promising technologies of the future. In case of large complex systems, the speed can be increased multiple times using FPGAs as it focuses on parallel execution. FPGA stands for Field Programmable Gate Array. It is a combination of various arrays of logic elements, programmable interconnects and the input and output ports and using these, it is programmed to FPGA to perform several tasks ranging from blinking a simple LED to the large control systems for various satellites. Now the main task is to program the FPGA device in order to perform these tasks. There are a number of ways in which FPGAs can be programmed which include:

Programming in HDLs(hardware descriptive languages) among which Verilog and VHDL are the most important.

FPGA are available in the market from various vendors like Xilinx, Altera, Lattice Semiconductor, Microsemi, QuickLogic, etc.

The control system designed using these software can be then burned into the Xilinx FPGA board for our required application.

XILINX SYSTEM GENERATOR allows us to design and implement high performance DSP systems into FPGA(Field Programmable Gate Array) with the help of simulink. It provides a set of simulink blocks which can be used to perform several hardware operations which can be easily implemented on the different Xilinx FPGAs. FPGAs are semiconductor devices made up of CLBs (Configurable Logic Blocks) which are connected together with the help of programmable interconnects. They can be reprogrammed depending upon their application or requirement after manufacturing and can also be remotely handled.

They have a wide range of application like in Aerospace, defense, consumer electronics, handling large amount of data, audio, automotive, high performance computing and storage of a large amount of data, wired as well as wireless communication, video and image processing, industrial and medical etc.

Steps for designing a model using Xilinx System Generator are:

Step 1: Start System Generator with MATLAB.

Step 2: Create a DSP system in the Simulink environment using Simulink and System Generator.

Step 3: Simulate the DSP system using Simulink.

System requirements:

System Generator 14.7

Xilinx ISE Design Suite 14.7

MATLAB 2013a with Simulink

For implementing the MPPT technique using the Xilinx System Generator, separate library block sets are added in the MATLAB/ Simulink. A gateway in block is used to convert the simulink data types (integer, double or fixed point) into System generator data type (fixed point). It serves as an input to the Xilinx part of the Simlink design. Similarly, gateway out block is used to convert the fixed point values into the simulink values. Voltage and current of the PV array is taken as 32- bit input with the binary point of 16- bits. A gateway in block is used in between the PV array and the MPPT control in order to convert the simulink values into the corresponding system generator values. The duty cycle is calculated using the Xilinx System Generator block sets and then using the gateway out block it is converted back to the simulink data type and then gate pulses of frequency 50 kHz are generated and given to the Boost converter.

3.8 THREE PHASE VOLTAGE SOURCE CONVERTER (VSC)

A three- phase VSC connects the PV array output power into grid. The VSC consists of six IGBT switches & interfacing inductors. The control signals of VSI are generated by considering the voltage and frequency of grid & also output voltage of PV array. There are two types of control schemes used for grid connected VSC according to the waveform generation:

i) Current control
ii) Voltage control

3.8.1 CURRENT CONTROL TECHNIQUE OF VSC

Current control technique involves production of sinusoidal output current. In this type of control technique a reference waveform is generated and phase locked to the grid and the output of the inverter follows the reference current. In this control technique the output current is limited even when the output is short circuited.

3.8.2 VOLTAGE CONTROL TECHNIQUE OF VSC

Voltage control technique involves production of sinusoidal output voltage. The harmonic current demanded by the non- linear loads is supplied by these inverters. The controlling of the modulation index is required for the Voltage Control of VSC which in turn controls the VARs and the phase angle of inverter is controlled with respect to the grid to control the power. Since the harmonic current demand of the load is met by the inverter, so the harmonics as seen by the grid are reduced. The efficiency of the SPV system depends upon the accuracy and fast control of grid tied inverter.

3.9 CONTROL ALGORITHMS FOR CONTROL OF VSC IN SPV SYSTEMS

The idea behind the formulation of a control algorithm is to generate a reference current which is compared to the measured current so as to generate the gate pulses for switches in VSC. This reference current can be generated using a number of control algorithms. A few of these control algorithms are given below:

i) PBT(Power Balance Theory)
ii) SRF(Synchronous Reference Frame) control
iii) IRPT(Instantaneous Reactive Power Theory)
iv) Adaline based control technique
v) Single phase PQ theory
vi) QPLL(Quadrature Phase Locked Loop) based control algorithm
vii) EPLL(Enhanced Phase Locked Loop) based control algorithm etc.

These control algorithms can be formulated for power factor correction i.e. for unity power factor operation or for zero voltage regulation. Two control loops are used in the system, one to maintain the DC link voltage at a constant level (say 800V) of the VSC and the other for the regulation of the amplitude of the PCC voltage.

3.10 REGULATION OF DC LINK VOLTAGE IN VSC

In the control of grid tied PV system, a Proportional Integral controller is used which regulates the DC link voltage that ultimately controls the load current. The load voltage is first converted into three unit components using the equations:

$$v_{pa} = v_{la}/V_T \tag{3.17}$$

$$v_{pb} = v_{lb}/V_T \tag{3.18}$$

$$v_{pc} = v_{lc}/V_T \tag{3.19}$$

where,

v_{pa}, v_{pb}, v_{pc}: Unit components of load voltage

v_{la}, v_{lb}, v_{lc}: a, b, c components of load voltages

v_T: amplitude of three phase voltage at load terminal

where, the peak value of load terminal voltage is given by:

$$V_T = \sqrt{\frac{2}{3}} * (v_{la}^2 + v_{lb}^2 + v_{lc}^2) \tag{3.20}$$

The switching losses are calculated using the measured DC link voltage and reference (say 800V) and this difference is then provided to the PI controller. PI controller output represents the loss component of the system. It decides the amplitude of the reference waveform which is generated to take as a reference for the implementation of the control algorithm. The product of this amplitude and each of the unit components gives the instantaneous value of reference waveforms.

$$I_S^* = P_{loss} * v_{pa} + P_{loss} * v_{pb} + P_{loss} * v_{pc} \tag{3.21}$$

where,

P_{loss}: loss component of system

The actual grid current, i_s is compared to this reference waveform and the control pulses are generated. These generated pulses are supplied to the inverter as the gate pulses.

3.11 CONTROL OF GRID TIED INVERTER USING POWER BALANCE THEORY

In this method of control for VSC, the instantaneous power consumed by the load is used to obtain the fundamental load current component. The PCC line voltages, grid currents, load currents and DC link voltage are used for the generation of gate pulses. The grid voltages (v_{sa}, v_{sb}, v_{sc}) and the load currents (i_{la}, i_{lb}, i_{lc}) are used for the calculation of the instantaneous active and reactive powers of the load. The instantaneous active power of load is calculated as:

$$p_L = v_{sa} * i_{La} + v_{sb} * i_{Lb} + v_{sc} * i_{Lc} \tag{3.22}$$

Low pass filter extracts the DC component of this instantaneous active power. The fundamental real power component of load current is obtained using the following relation:

$$I_{lactive} = \frac{2*P_{L_{DC}}}{3*V_t} \qquad (3.23)$$

where,

$P_{lactive}$ = fundamental active power component,

v_T: amplitude of load terminal voltage

The active load current fundamental component and PI controller output which is used to regulate the DC link voltage, are added together and this forms the active power component of reference currents. Since the PI controller output of the DC link voltage is considered as the loss component of the system, so, the amplitude of the reference current fundamental active power component of is given by:

$$I_{active\_ref} = I_{lac} \quad + I_{loss} \qquad (3.24)$$

where,

I_{loss}: loss component of the system

The unit templates which are in- phase are extracted using the grid voltage, $V_{sa,b,c}$ as:

$$u_{sa} = \frac{v_{sa}}{V_t}; u_{sb} = \frac{v_{sb}}{V_t}; u_{sc} = \frac{v_{sc}}{V_t} \qquad (3.25)$$

where,

v_{sa}, v_{sb}, v_{sc}: a, b, c components of grid voltage

The in-phase unit templates are used to find out the instantaneous value of fundamental in phase component of reference current, which is given as:

$$i_{sa\_ref} = u_{sa} * I_{active\_ref} \qquad (3.26)$$

$$i_{sb} = u_{sb} * I_{active\_ref} \qquad (3.27)$$

$$i_{sc} = u_{sc} * I_{active\_ref} \qquad (3.28)$$

Now, the actual grid currents and these reference supply currents are compared, and this difference is further used to generate the pulses which are given to the inverter as the gate pulses.

3.12 CONCLUSION

In this chapter a brief description of the photovoltaic system, and its different topologies are discussed. The PV cell, module and array connections are described. It also describes the Boost converter, MPPT technique and the 3- phase VSI control techniques.

CHAPTER 4

MATLAB MODELING OF GRID CONNECTED SOLAR PV SYSTEMS AND SIMULATION

4.1 INTRODUCTION

In this chapter mathematical modeling of PV cell and array have been described. The P-V and I-V characteristics of the PV array are discussed. P&O MPPT algorithm for increasing efficiency of SPV system is demonstrated through modeling and simulation. The characteristics of the MPPT have been presented along with the XSG based simulation. Simulation of the grid connected PV system is discussed with following two inverter control techniques:

1) Inverter control using simple PI control
2) Inverter control using Power Balance Theory

4.2 MATHEMATICAL MODELING OF PV CELL

The single diode model of photovoltaic cell is shown in Fig.1. Current source (I_{PH}) represents the photocurrent of the cell. The intrinsic shunt resistance of the cell is represented by R_{SH} and its value is quite large. The intrinsic series resistance of the cell is represented by R_S and its value is usually very small and can be neglected to simplify the analysis.

A PV cell model can be shown as:

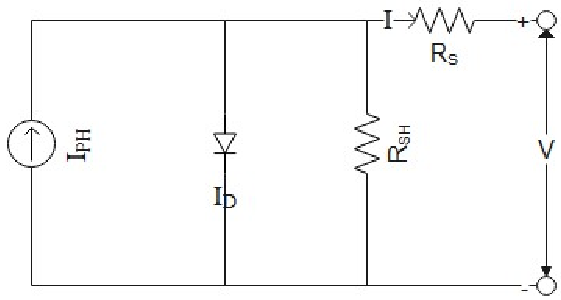

Fig.4.1 Single diode PV cell equivalent circuit

Using Kirchhoff's current law, the following current equation is obtained:

$$I = I_{PH} - I_D - I_{SH} \quad (4.1)$$

where:

I = Output current of the PV cell

I_{PH} = Photo generated current

I_D = Current across the diode

I_{SH} = Shunt current

According to the Shockley diode equation, diode current,

$$I_D = I_0(\exp\left(\frac{q(V+IR_S)}{nkT}\right) - 1 \tag{4.2}$$

where:

q = Electron's charge = $1.6 \times 10^{-19}C$

I_0 = Reverse saturation current

V = Voltage across output terminals

R_S = Series resistance

n = Diode ideality factor(n = 1 for Ge, n= 2 for Si)

T = Absolute temperature

The shunt current is given by,

$$I_{SH} = \frac{V+IR_S}{R_{SH}} \tag{4.3}$$

Substituting eq. (4.2) and (4.3) in eq. (4.1), the output current of the PV cell,

$$I = I_{PH} - I_0\left(\exp\left(\frac{q(V+IR_S)}{\boldsymbol{nkT}} - 1\right)\right) - I_{SH} \tag{4.4}$$

A PV cell has a maximum open circuit voltage at zero output current and it is given by Voc. It has a short circuit current denoted by Isc, at zero output voltage. No power is generated during open circuit or short circuit condition.

4.3 PV ARRAY MODELING

An equivalent PV array circuit is shown in Fig. 4.6

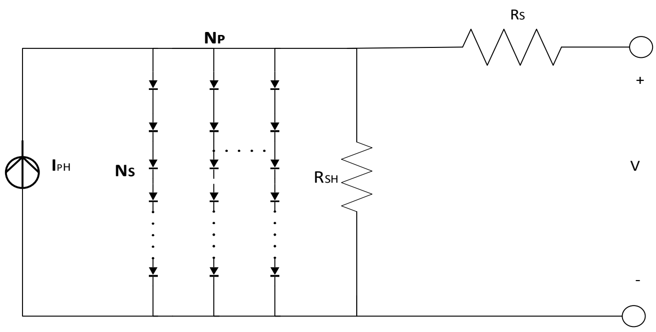

Fig.4.2 Equivalent circuit of PV array

Module photocurrent I_{PH} is given by,

$$I_{PH} = [I_{SC} + K_i(T - 298)]\frac{G}{1000} \quad (4.5)$$

where,

I_{PH} : module photo current (A)

K_i : short-circuit current of the cell obtained at 25°C and 1000 W/m^2

T : operating temperature (K)

G : solar irradiation (W/m^2)

Reverse saturation current of the module, I_{RS} is given by,

$$I_{RS} = \frac{I_{SC}}{\exp\left(\frac{qV_{OC}}{nn_S k.T}\right) - 1} \quad (4.6)$$

where,

q : electron's charge(C) = $1.6 \times 10^{-19} C$

V_{OC} : open circuit voltage (V) = 64.2 V

n_S : number of cells connected in series = 96

n = Diode ideality factor

k = Boltzmann's constant(J/K)

Module saturation current, I_0 is given by,

$$I_0 = I_{RS}\left(\frac{T}{T_n}\right)^3 \exp\left(\frac{qE_{g0(\frac{1}{T_n}-\frac{1}{T})}}{nk}\right) \quad (4.7)$$

where,

T_n = nominal temperature

E_{g0} = semiconductor band gap energy

Module shunt current, I_{SH} is

$$I_{SH} = \frac{V + IR_S}{R_{SH}} \quad (4.8)$$

Module output current, I is given by

$$I = I_{PH} - I_0\left(\exp\left(\frac{q(V + IR_S)}{nkN_S T} - 1\right)\right) - I_{SH} \quad (4.9)$$

where,

N_P = number of parallel connected PV modules

R_S = series resistance (Ω)

R_{SH} = shunt resistance (Ω)

TABLE 4.1 DETAILS OF PV ARRAY CONFIGURATION

PV array Parameters	Value
Number of series connected modules(N_S)	6
Number of parallel connected modules(N_P)	27
Maximum PV power (P_{mp})	50kW
Voltage at MPP of each module (V_{mp})	54.7V
Current at MPP of each module (I_{mp})	5.58A

4.4 P-V AND I-V CHARACTERISTICS OF PV ARRAY

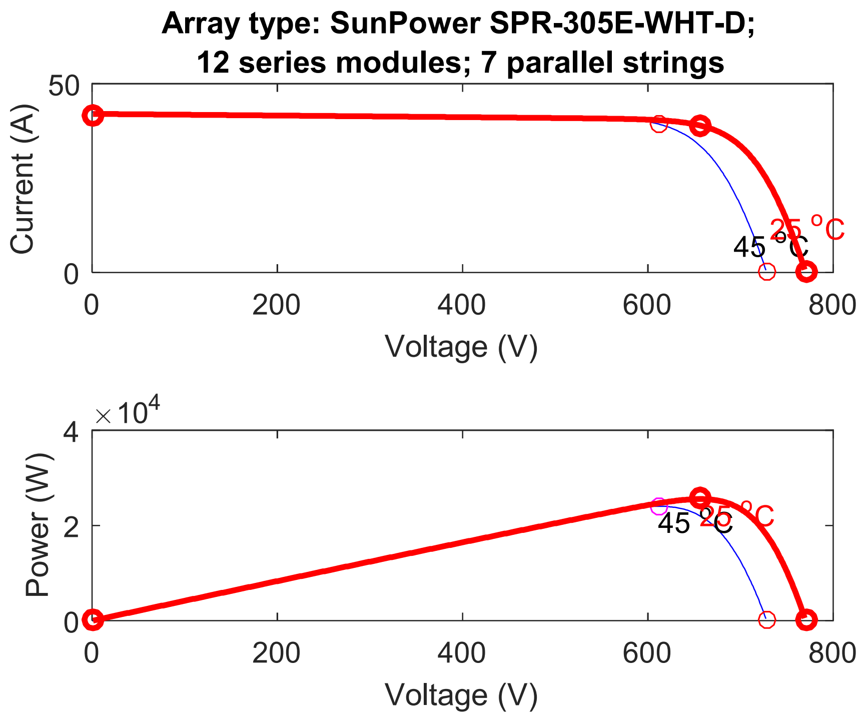

Fig. 4.3 I-V and P-V curves of PV array

Fig. 4.3 shows the I-V and P-V curves of PV array. For the analysis, the first quadrant of curves is considered because it is the only quadrant in which the power is actually generated by the PV cell. The starting point of the I-V curve is the I_{SC} (short circuit current). At this point, the voltage is zero. The end point of the P-V and I-V curves is V_{OC}(open circuit voltage). The current at this point is equal to zero. At both the points, short circuit and open circuit, the power output is zero. And at some point between these two, the power output is maximum.

4.5 P-V AND I-V CHARACTERISTICS OF PHOTOVOLTAIC MODULE WITH VARYING IRRADIANCE

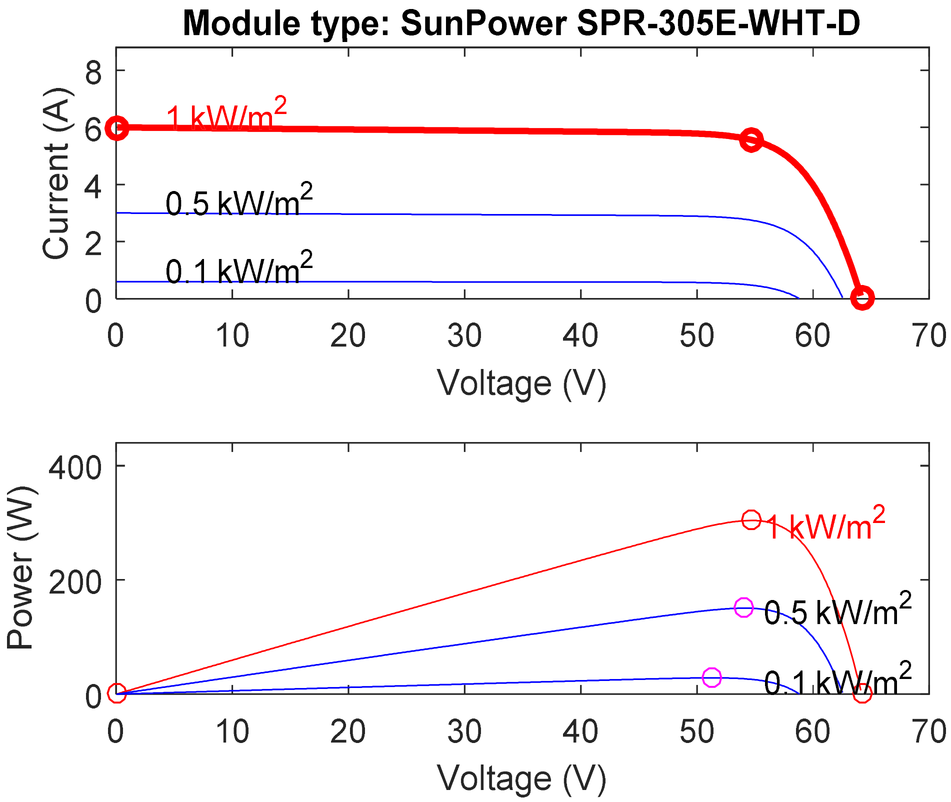

Fig.4.4 I-V and P-V curves with changing irradiance

Fig. 4.4 shows the I-V and P-V curves of PV module with varying irradiance. It shows that when the solar irradiance is increased, the short circuit current as well as the open circuit voltage of the solar module increases.

4.6 P-V AND I-V CHARACTERISTICS OF PHOTOVOLTAIC MODULE WITH VARYING TEMPERATURE

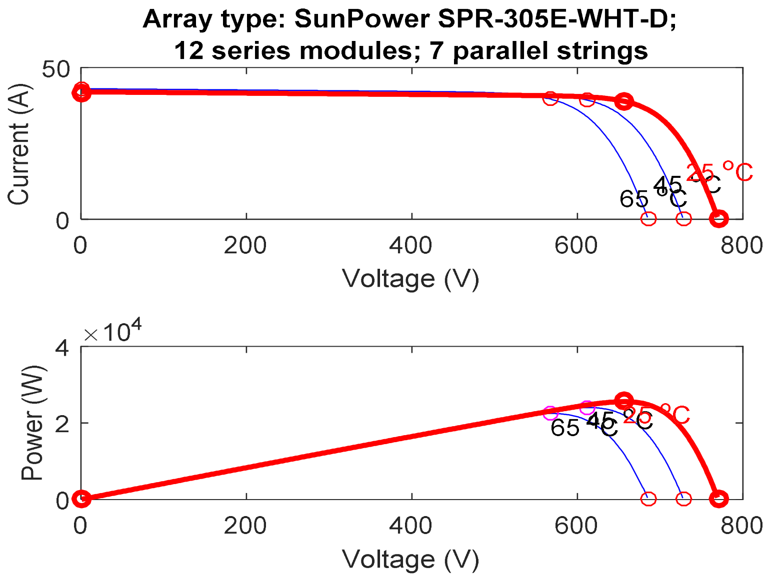

Fig.4.5 I-V and P-V characteristics with varying temperature

Fig. 4.5 shows the I-V and P-V characteristics of PV module with varying temperature. It shows that on increasing the module temperature, the open circuit voltage gets decreased, and the short circuit current gets increased.

4.7 P-V AND I-V CHARACTERISTICS OF PV MODULE USED IN THE SIMULATION STUDY OF GRID TIED SPV SYSTEM

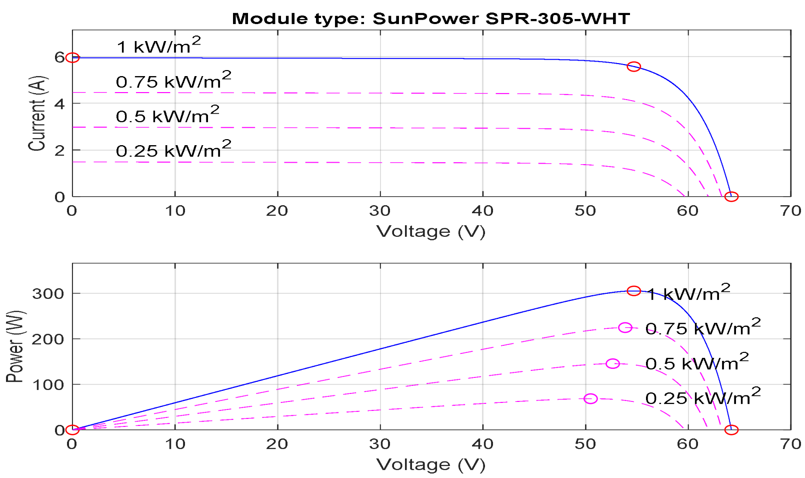

Fig. 4.6 PV module I-V AND P-V curves used in the system

Fig. 4.6 shows the P-V and I-V characteristics of the PV module used in the system at four different values of irradiances 0.2kW/m^2, 0.5 kW/m^2, 0.75 kW/m^2 and 1 kW/m^2. As the irradiance is increased, the short circuit current increases. Also the P-V curve shows that the maximum power or peak power increases as the irradiance is increased.

4.8 P-V AND I-V CHARACTERISTICS OF PV ARRAY

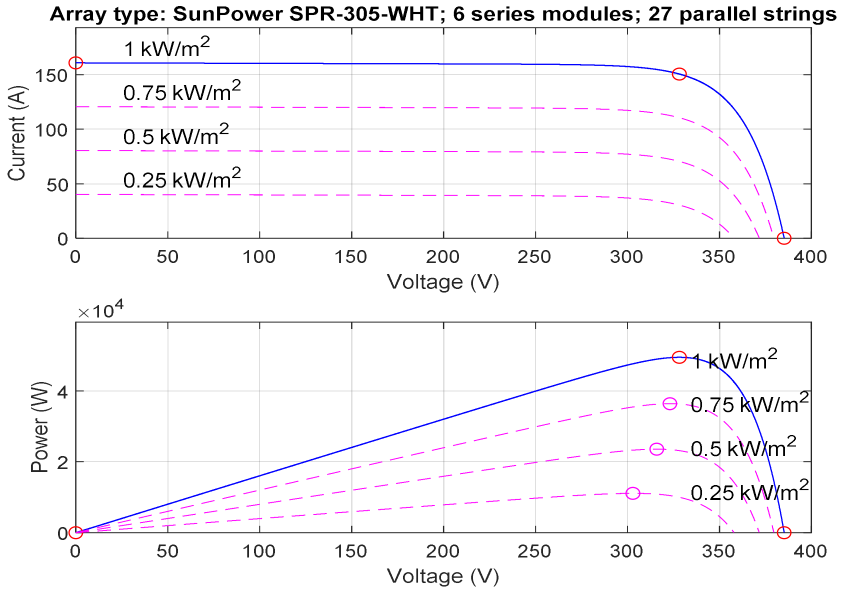

Fig. 4.7 I-V and P-V characteristics of PV array used in the system

Fig. 4.7 shows the I-V and P-V characteristics of the PV array which have been used in the system. I-V and P-V characteristics at four different irradiances (1000W/m^2, 750W/m^2, 500W/m^2, 250W/m^2) are shown in the figure.

4.9 DESIGN OF BOOST CONVERTER

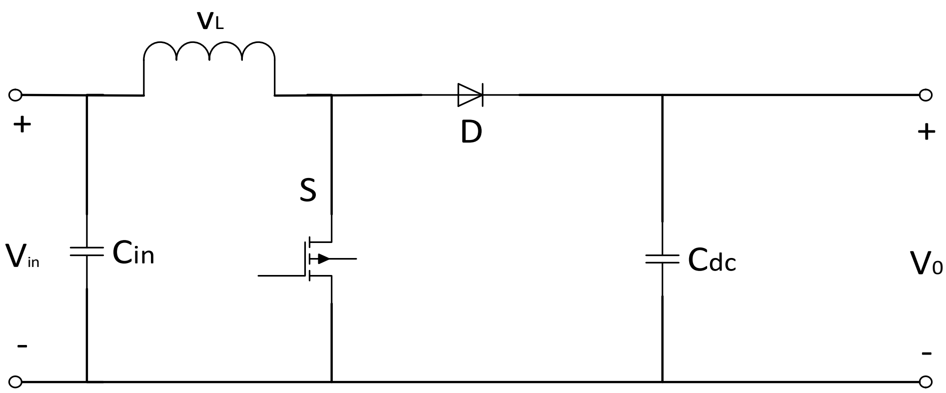

Fig.4.8 Boost converter circuit diagram used in the system

Assuming the following given design specifications, the current ripple lie between 0.3 and 0.5 times of the inductor current i.e.

$$0.3I_L \leq \triangle I_L \leq 0.5I_L$$

& voltage ripple should be nearly 2%, i.e.

$$\triangle V_0 \leq 2\%\ of\ V_o$$

Switching frequency = 5 kHz

Duty cycle,

$$D = \frac{V_o - V_{in}}{V_o} \tag{4.10}$$

$$D = \frac{800 - 328.2}{800} = 0.59$$

Value of inductor,

$$L = \frac{V_{mp}.D}{f_s.\triangle I_L} \tag{4.11}$$

$$= \frac{328.2 * 0.59}{5000 * 0.5 * 150.66}$$

$$= 0.514mH$$

Chosen value of inductor in the system = 1.45mH

Value of input capacitance,

$$C_{in} = \frac{D}{8 * {f_s}^2 * L * 0.01} \tag{4.12}$$

$$= \frac{0.59}{8 * 5000^2 * 0.513 * 0.001 * 0.01}$$

$$= 0.00057H$$

$$= 570\mu H$$

Chosen value of input capacitance = 1000µH

Value of output capacitance or DC link capacitance,

$$C_{dc} = \frac{I_0 * D}{\Delta V_0 * f_{sw}} \tag{4.13}$$

$$= \frac{62.5 * 0.59}{0.02 * 800 * 5000}$$

$$= 0.0004609\ F$$

$$= 460.9\mu F$$

Chosen value of DC link capacitor = 1000 μF

Value of DC link voltage,

$$V_{dc} = \frac{(2\sqrt{2}.V_{L-L})}{\sqrt{3}.m} \tag{4.14}$$

$$= \frac{2\sqrt{2} * 415}{\sqrt{3} * 0.9}$$

$$= 752.99V$$

Chosen value of DC- link voltage = 800V

where,

V_{L-L} : line voltage of inverter

m : modulation index

4.10 SIMULINK MODEL OF PV ARRAY AND BOOST CONVERTER

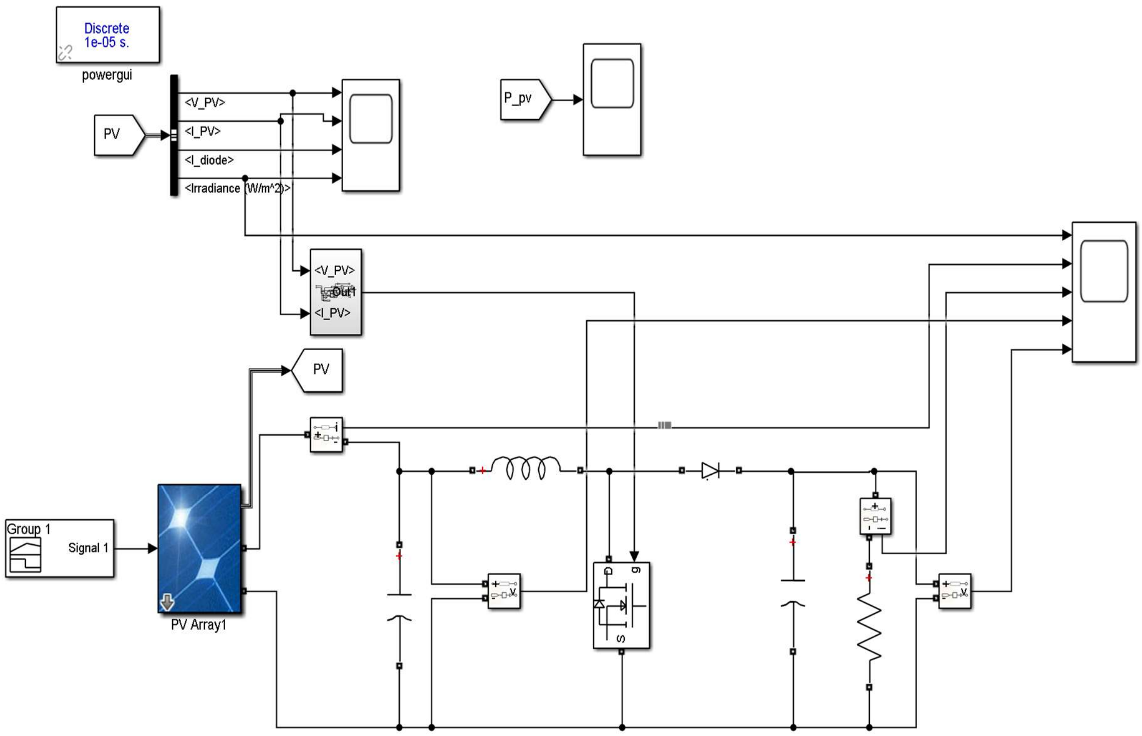

Fig.4.9 Simulink model of a PV array & boost converter

Fig. 4.9 shows simulink model of the Boost converter with P&O MPPT control. The boost converter switching signals are generated using the P&O MPPT control.A MATLAB/ Simulink model of MPPT algorithm is also developed and discussed. A switching frequency of 5 kHz is used in the system. Measurement of the input and output current and voltages of the Boost converter is done using voltage and current measurement blocks.

TABLE 4.2 PV ARRAY PARAMETERS USED IN THE SYSTEM

Parameters	Values
Number of cells per module	96
Number of modules connected in series per string	6
Number of strings in parallel	27
Open circuit (OC) voltage	64.2 V
Short circuit (SC) current	5.96 A
Voltage at MPP	54.7 V
Current at MPP	5.58 A

TABLE 4.3 BOOST CONVERTER PARAMETERS USED IN THE SYSTEM

Parameters	Values
Input capacitance, C_{in}	1000µF
Inductance, L	1.45mH
Output capacitance, C_{dc}	1000µF
Switching frequency, f_s	5kHz

4.11 SIMULINK MODEL OF PERTURB AND OBSERVE ALGORITHM

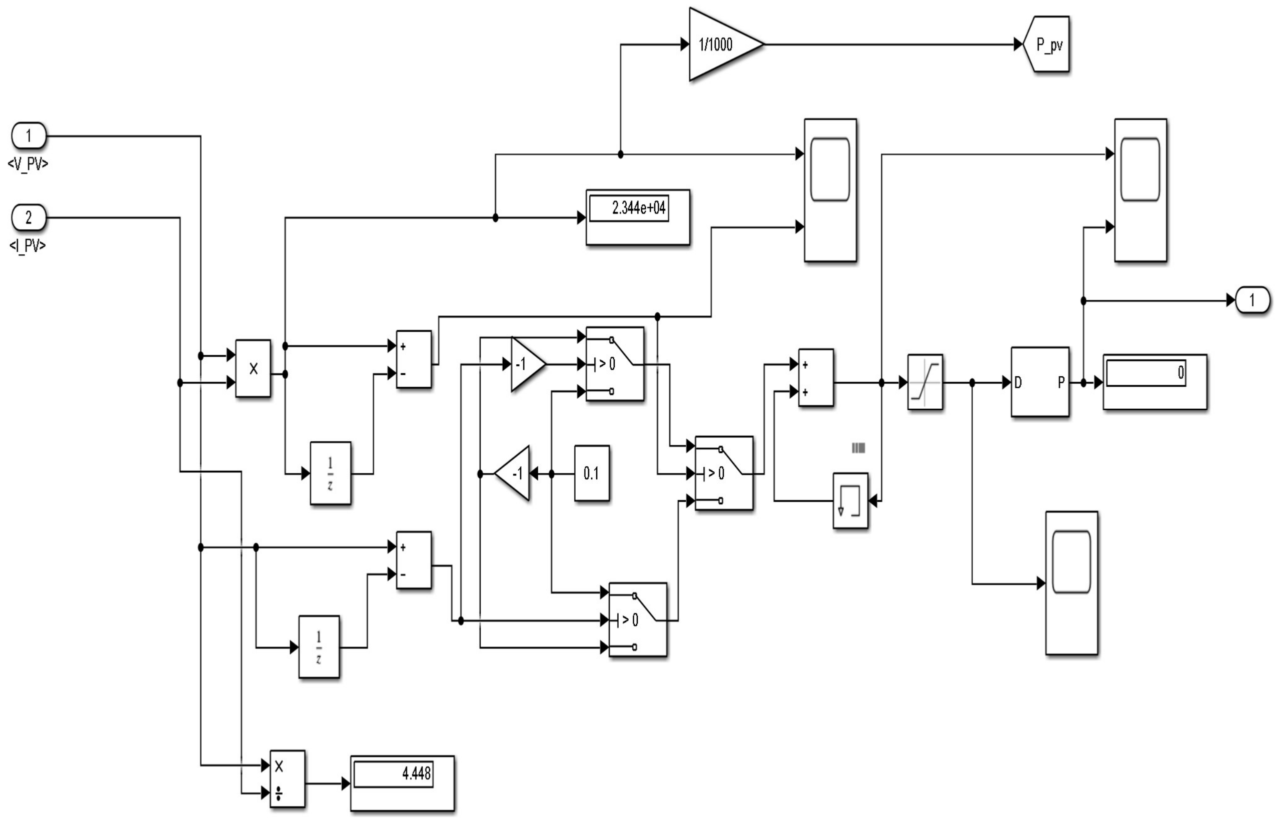

Fig.4.10 Simulink model of P and O algorithm

Fig. 4.10 shows the simulink model of the P&O algorithm used in the system. Voltage and current inputs to the MPPT algorithm are taken from the PV array output. A perturbation of 0.1 is taken in the PV array voltage during the implementation of the algorithm. The switching signal with a frequency of 5 kHz is generated and given as a gate signal to the Boost converter.

4.12 SIMULATION RESULTS AND DISCUSSION

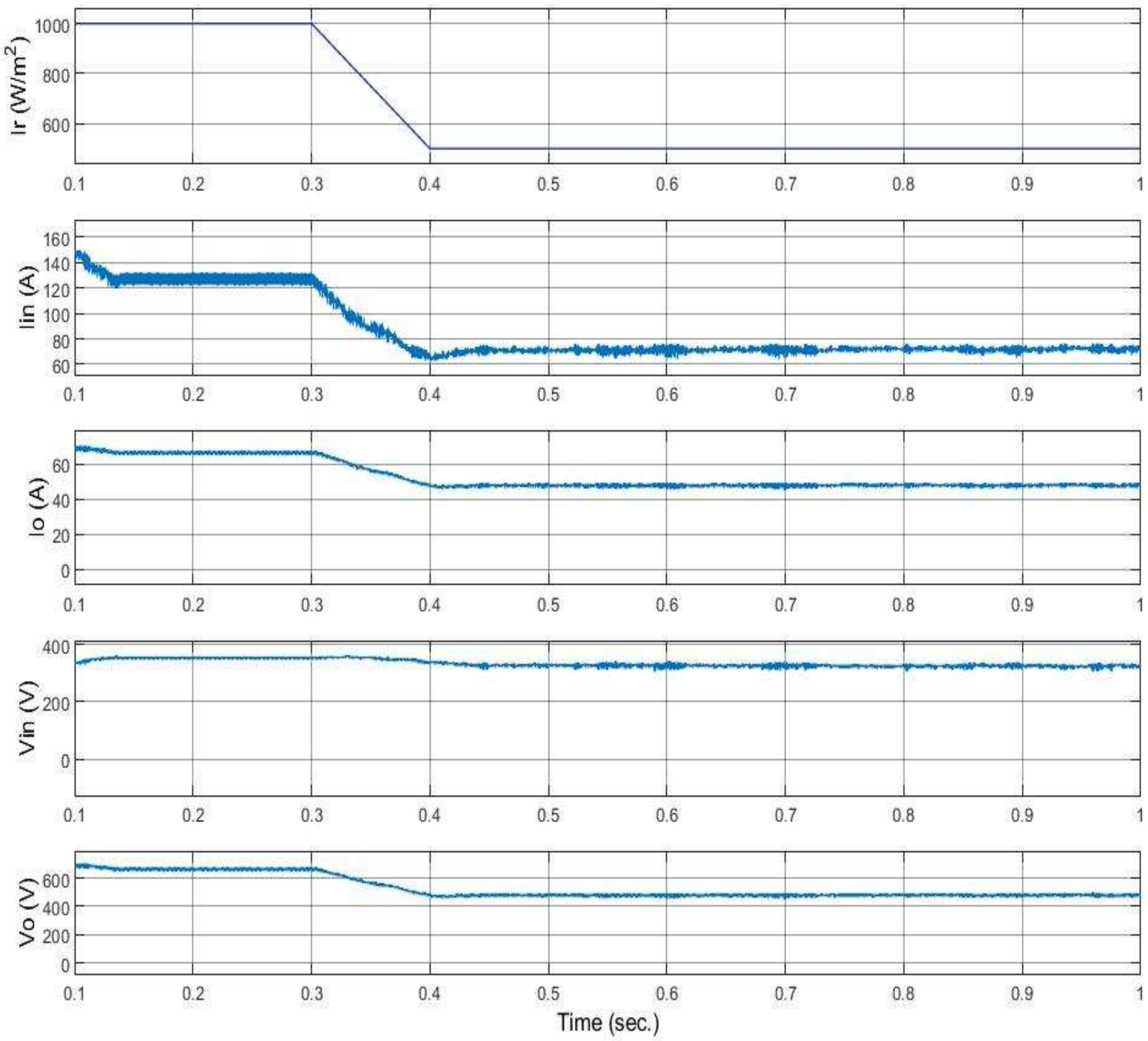

Fig. 4.11Transient response of PV array and Boost converter

Fig. 4.11 shows the irradiance (Ir) received by the PV array,input current (Iin), output current (Io), input voltage (Vin) and output voltage (Vo) waveforms of the Boost converter. It shows that when the irradiance is 1000 W/m^2, the output voltage of the Boost converter is 700V and when the irradiance is reduced to 500W/m^2, the output of the Boost converter is 480V, and is still greater than the input voltage.

4.13 XILINX SYSTEM GENERATOR BASED SIMULINK MODEL OF P AND O ALGORITHM

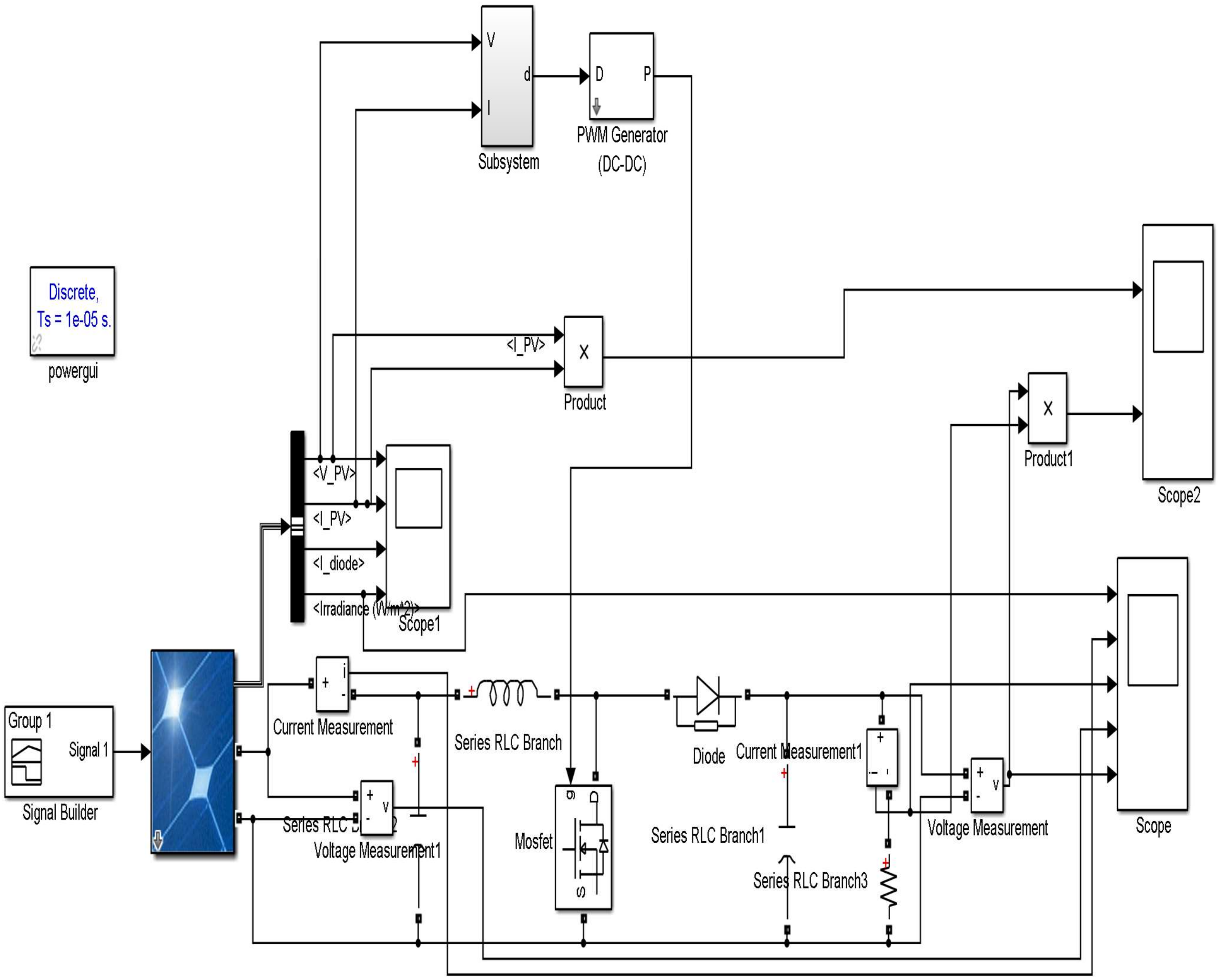

Fig.4.12 Simulink model of Boost converter using XSG based P&O MPPT control

Fig. 4.12 shows the simulink model of the Xilinx System Generator based P&O MPPT control of Boost converter. The PV array operates at the varying irradiance which is provided by the signal builder block. The MOSFET used in the Boost converter receives the control gate pulses at a switching frequency of 5 kHz from the XSG based P&O MPPT algorithm.

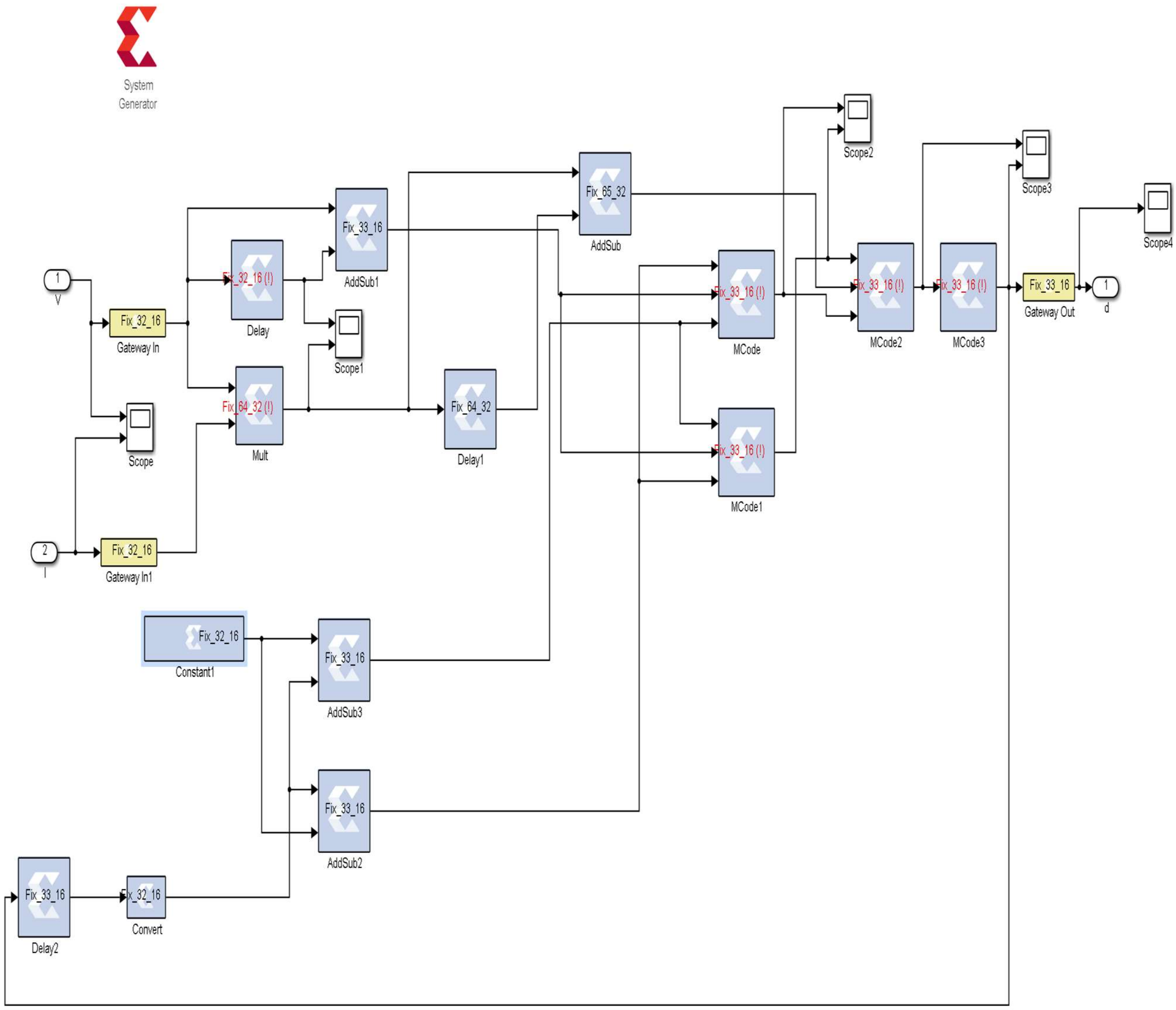

Fig. 4.13 XSG based simulink model of P and O algorithm

Fig. 4.13 shows the P&O MPPT algorithm based on Xilinx System Generator. The voltage and current values, which are taken as input to the XSG based control algorithm, are first made to enter into the gateway in block of the XSG which converts the Simulink values into the form recognized by the system generator blocks. The control algorithm is then implemented and the output of this control algorithm is made to pass through the gateway out block of the XSG which converts the signal back to the simulink which is then converted into the switching signal and then given to the Boost converter.

4.14 SIMULATION RESULTS OF MPPT IMPLEMENTATION IN XILINX

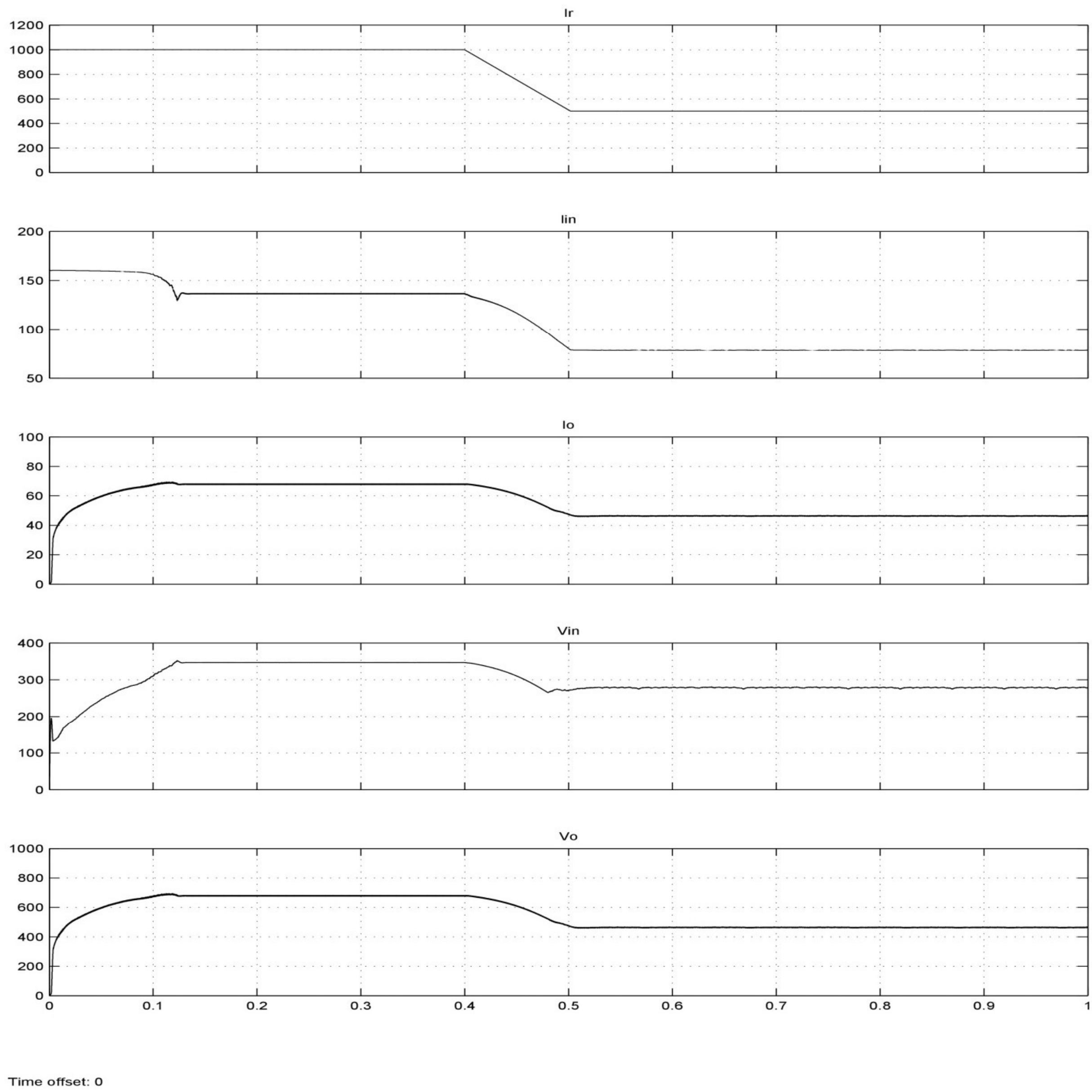

Fig. 4.14 Waveforms related to the Boost converter with XSG based control

Fig. 4.14 shows the irradiance (Ir), along with the boost converter input current (Iin), output current (Io), input voltage (Vin) and output voltage (Vo) waveforms related to the XSG based implementation of the P&O MPPT algorithm. When irradiance is 1000W/m^2, the voltage output of the Boost converter is 680V and when the irradiance value is decreased to 500W/m^2, at t = 0.5s, the output voltage becomes 460V and is still more than the voltage at the input side of the converter.

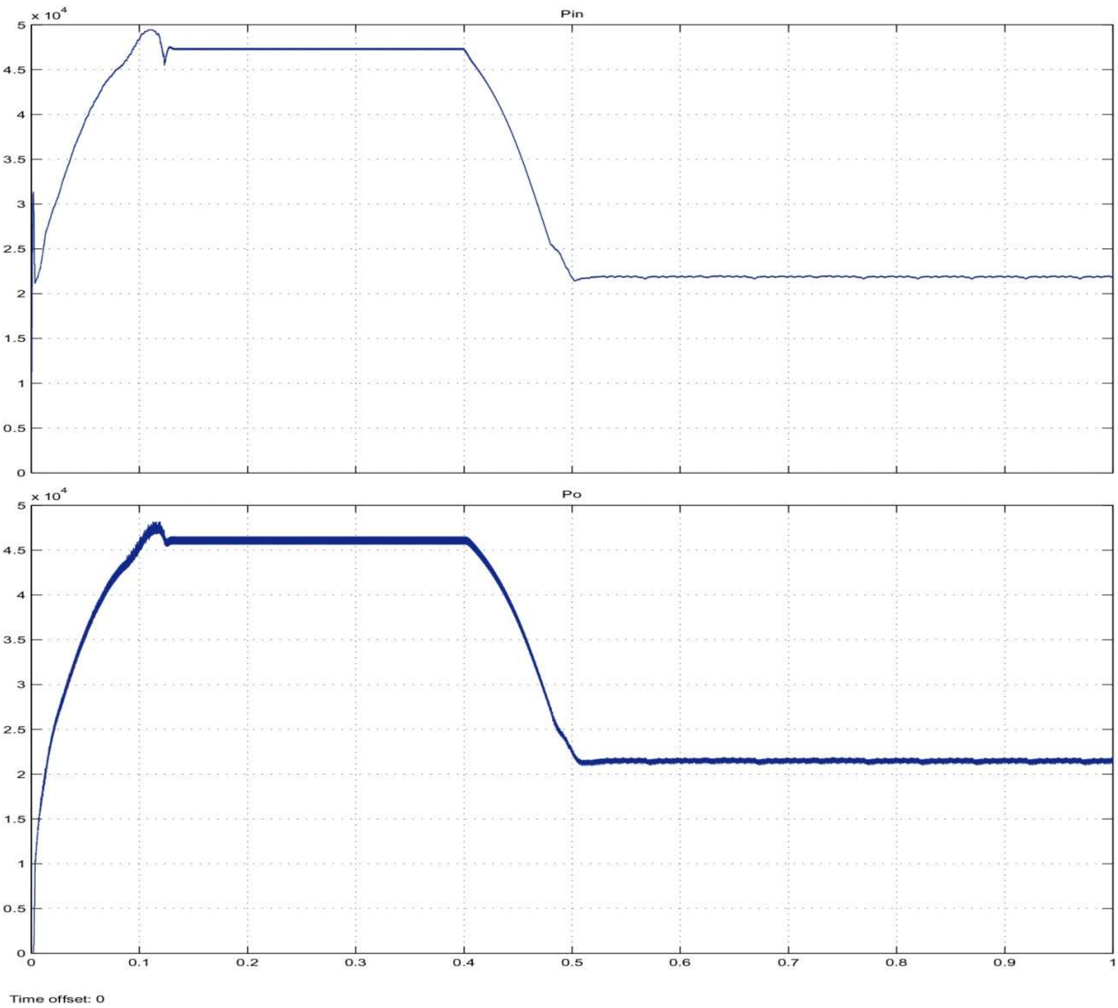

Fig. 4.15 Boost converter input and output power waveforms

Fig. 4.15 shows the input and output power of the Boost converter. When the irradiance value is $1000W/m^2$, the input power is 47.3kW and the output power is 45.7kW and as the irradiance is decreased to $500W/m^2$, the input power becomes 21.9kW and output power becomes 21.6kW.

4.15 SIMULINK MODEL OF GRID TIED PV SYSTEM

TABLE 4.4 PARAMETERS USED IN THE SYSTEM

SYSTEM PARAMETERS	VALUES
3- phase AC source	415V, 0.001mH
Interfacing inductor value, L_i	3.5mH
Filter inductance, L_f	2.5mH
Load	i) 3- phase Linear load: 415V, 24kVA, 0.8 pf lagging ii) 3- phase non linear load: 20Ω, 80mH
DC link capacitor	1000μF
Grid frequency, f_s	50Hz
PV array	P_{pv} = 49.45kW, Vmpp = 328.2V, Impp = 150.66A
Boost converter input capacitance, C_{in}	100μF
Inductor value for Boost converter	1.45mH

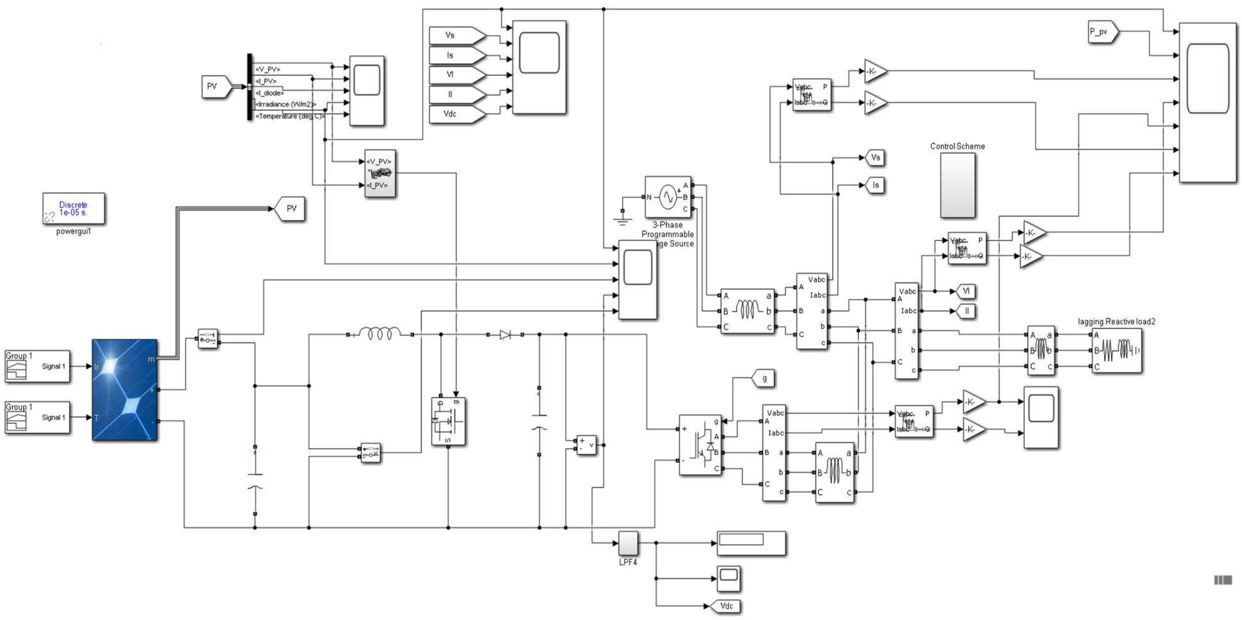

Fig.4.16 Simulink model of grid integrated PV system using a simple PI control of inverter and connected to 3-phase R-L load

Fig. 4.16 shows the simlink model of grid integrated PV system. A simple PI controller based control algorithm for the control of grid tied inverter connected to an R-L load. A PV system of 50kW is used in the system. The DC output produced by the PV array is connected to the Boost converter which is further connected to the input terminals of the inverter. P&O MPPT algorithm is implemented and the output switching pulses produced by the algorithm are given to the Boost converter. The control of inverter is developed using the simple PI controller at DC link and unit current template derived from the grid voltage. The unit templates (v_{pa}, v_{pb}, v_{pc}) are obtained by dividing grid voltage by its magnitude. Reference grid currents are generate by multiplying unit templates to PI controller output at DC link. The reference currents are compared to actual line currents of grid line current response to generate PWM control signals for VSC.

4.16 SIMULINK MODEL OF CONTROL OF GRID TIED INVERTER USING A SIMPLE PI CONTROLLER

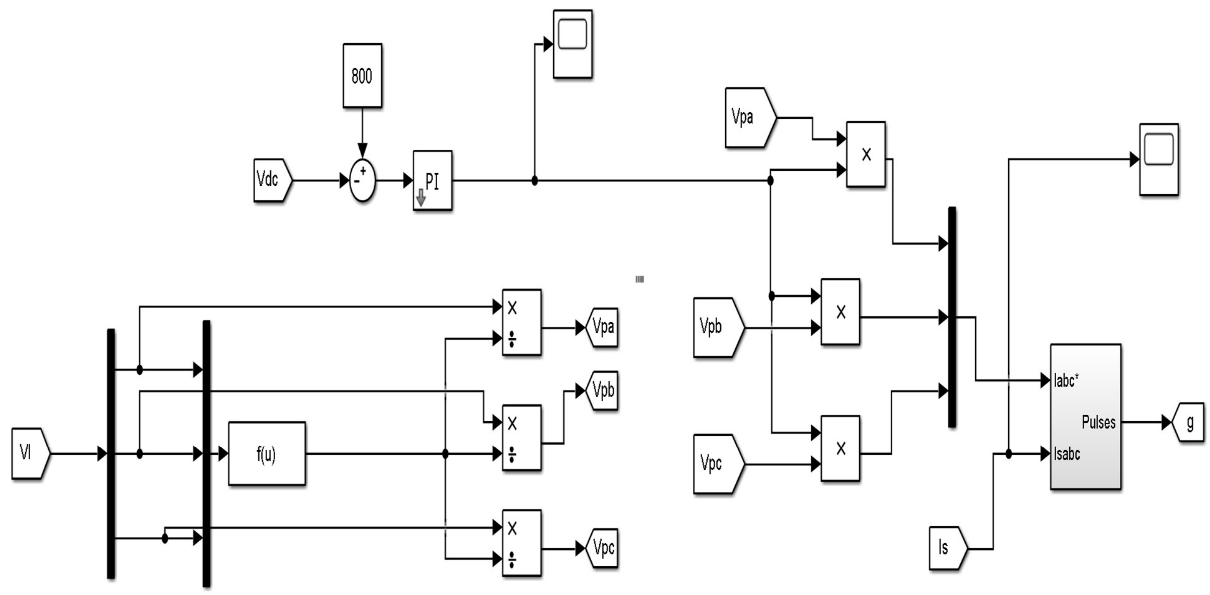

Fig.4.17 Simulink model of simple PI control technique of grid tied inverter

Fig. 4.17 shows the simulink model of the simple PI control for the control of the grid tied inverter used in the system. The control algorithm uses the load voltage, DC link voltage and the actual grid currents for the control of the grid tied inverter. The reference current waveform is generated whose magnitude is decided by the DC link voltage and the product of the unit templates obtained and the magnitude gives the reference waveform.

4.17 SIMULATION RESULTS OF GRID TIED PV SYSTEM USING SIMPLE PI CONTROL

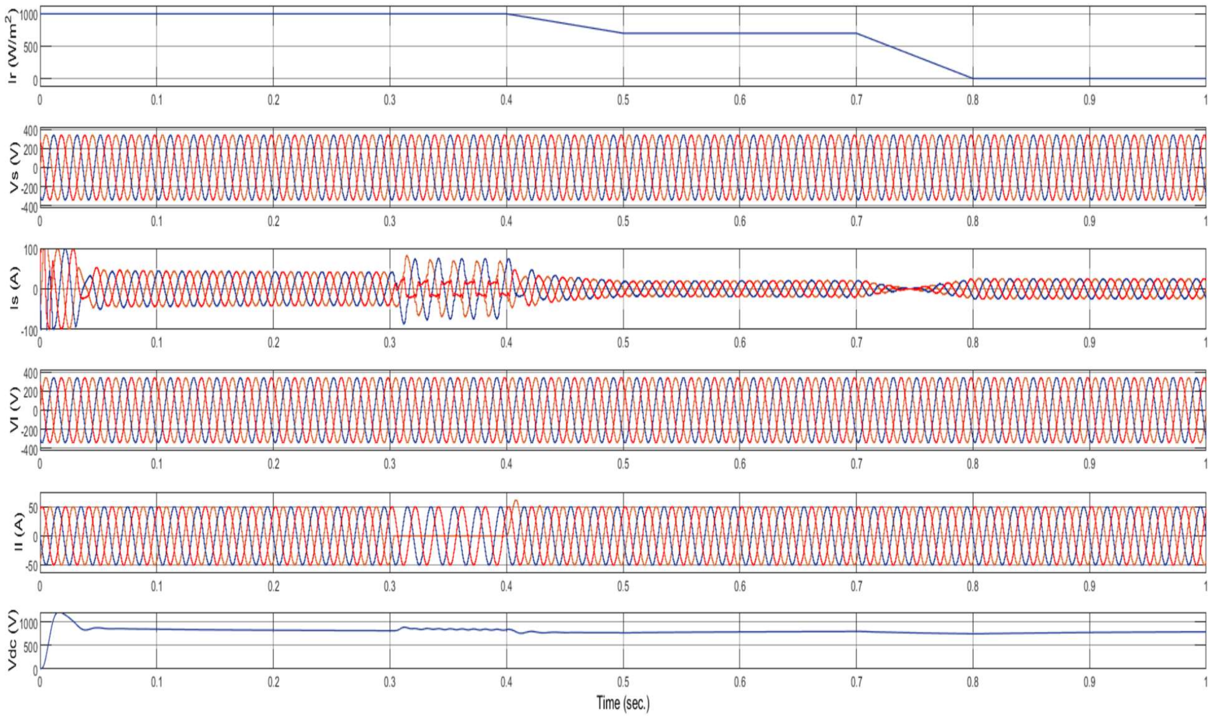

Fig.4.18 Waveforms related to the grid tied PV system with simple PI based control of inverter and connected to a 3- phase inductive load

Fig. 4.18 shows grid voltage (V_{sa}, V_{sb}, V_{sc}), grid current (I_{sa}, I_{sb}, I_{sc}), load voltage (V_{la}, V_{lb}, V_{lc}), load current (I_{la}, I_{lb}, I_{lc}), and DC-link voltage (V_{dc}) waveforms with simple PI based control of grid tied inverter connected to inductive load. For $0 < t < 0.4s$, the irradiance is 1000W/m^2 when this irradiance is reduced to 700W/m^2 for $0.5s < t < 0.7s$, the grid current reduces but the PCC voltage, load current and voltage at the DC link remain the same. For $0.8s < t < 1s$, the irradiance is further reduced to 0 W/m^2. For this time interval the grid currents reverse. A phase is switched off between t=0.3s to t=0.4s.The waveforms show that the load current successfully follows the voltage waveform and hence unity power factor is maintained at PCC. Also a constant DC link voltage is maintained at the PCC. This demonstrates that the control technique is successfully implemented for power factor correction mode of operation.

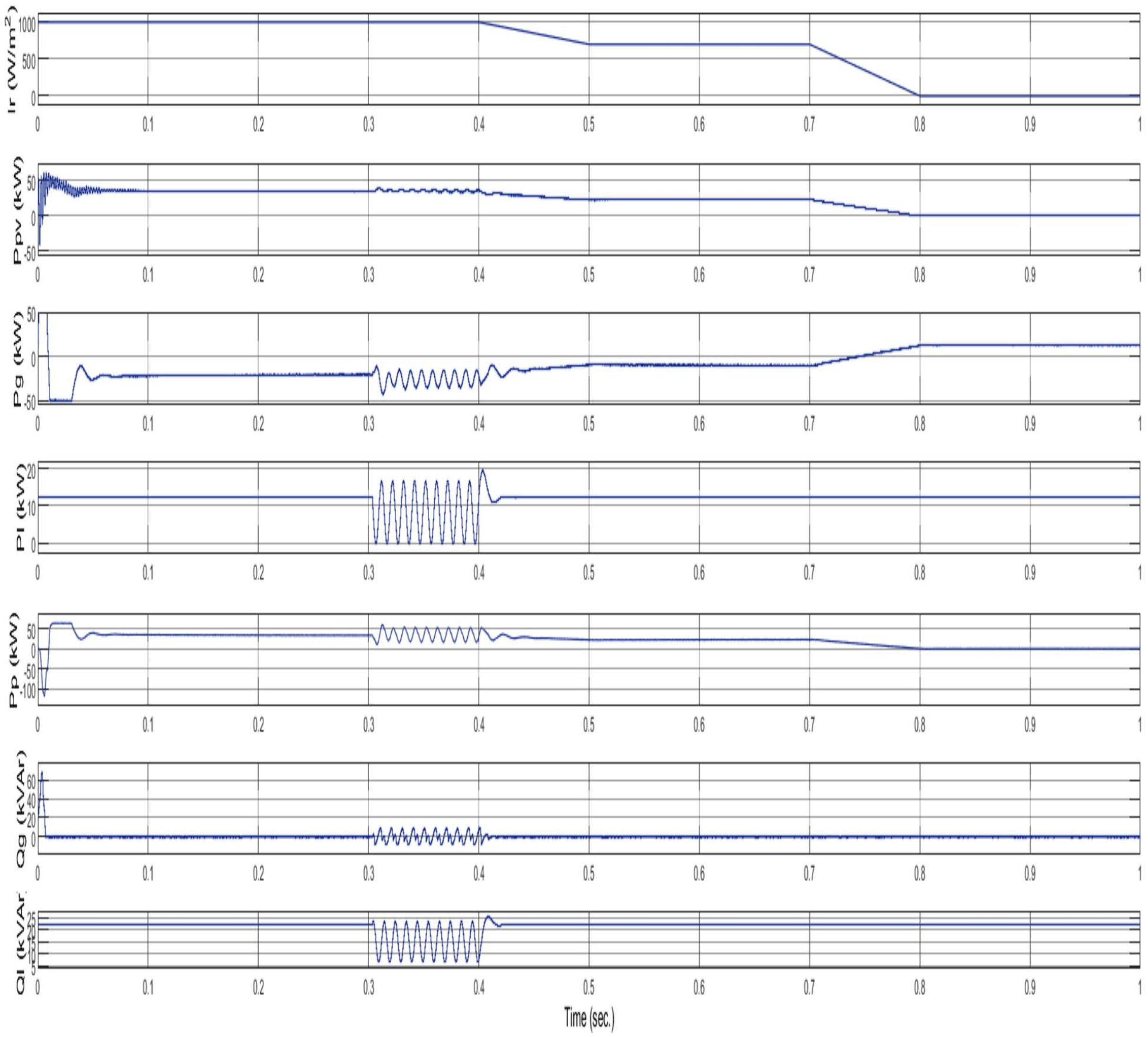

Fig. 4.19 Power flow in SPV system

Fig. 4.19 shows the power supplied by the PV array (Ppv), active power of the grid (Pg), active power of the load (Pl), reactive power of the grid (Qg) and reactive power of the load (Ql) when the simple PI based control algorithm is used for the control of grid tied inverter. For $0 \leq t \leq 0.4$s, the irradiance is 1000W/m^2, the active power demanded by the load is 12kW. The active power supplied by the PV system is higher than the active power required by the load, so the remaining active power is supplied to the grid. For time $0.5s < t < 0.7s$, the irradiance is 700W/m^2, and then for $t > 0.8s$, the irradiance is further reduced to 0W/m^2. In this time span the power generated by the PV array is zero so the grid delivers the active power to the load.

4.18 SIMULINK MODEL OF GRID TIED PV SYSTEM CONNECTED TO NON- LINEAR LOAD

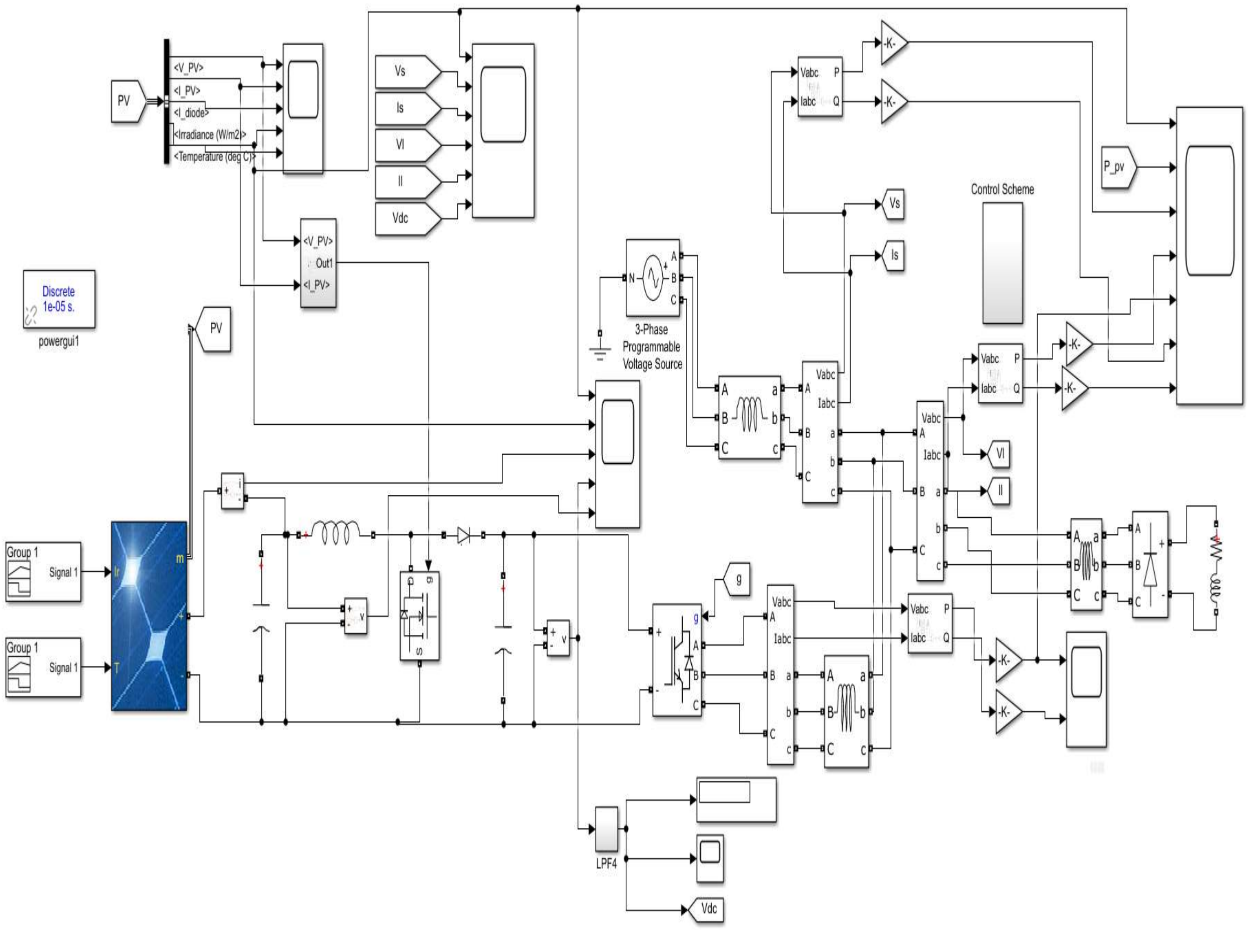

Fig. 4.20 Simulink model of grid tied PV system connected to non- linear load

Fig. 4.20 shows the simulink model of the grid tied PV system using simple PI control for the inverter and delivering power to a non- linear load. The PV array of 50kW is used in the system and the output of the PV array is given as an input to the Boost converter. A P&O technique is used for the MPPT control and the dc to dc converter output is connected to the input terminals of the inverter which converts the DC power into the corresponding AC power. The output of the inverter is connected to the grid as well as the load.

4.19 SIMULATION RESULTS OF GRID TIED INVERTER CONNECTED TO NON- LINEAR LOAD

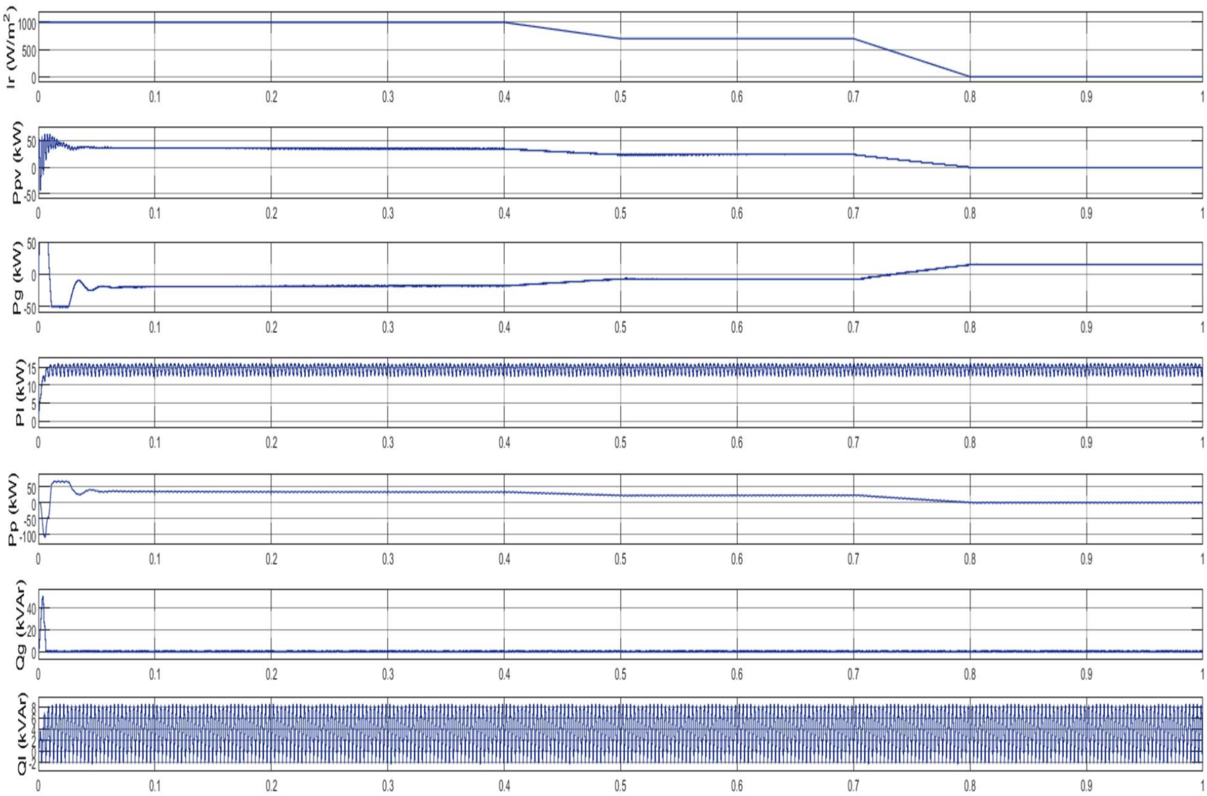

Fig.4.21 Simulation results of grid tied inverter connected to non- linear load

Fig. 4.21 shows the power supplied by the PV array (Ppv), active power of the grid (Pg), active power of non- linear load (Pl), reactive power of grid (Qg) and reactive power of non- linear load (Ql) when the simple PI based control algorithm is used for the control of grid tied inverter. As the control of the inverter is implemented in such a way that the reactive power is supplied by the PV system at all times, so the reactive power supplied by the grid is zero. For $0 \leq t \leq 0.4$s, the irradiance is 1000W/m^2, the active power supplied by the PV system is higher than the active power required by the non- linear load, so the remaining active power is supplied to the grid. For time 0.5s $< t < 0.7$s, the irradiance is decreased to 700 W/m^2 so the active power supplied by the PV array also reduces, so less amount of excess power is supplied to the grid. For 0.8s $< t <$ 1s the irradiance is reduced to 0W/m^2 so the solar PV output is zero because of which the active power supplied by the PV system becomes zero so, the active power demanded by the load is entirely supplied by the grid.

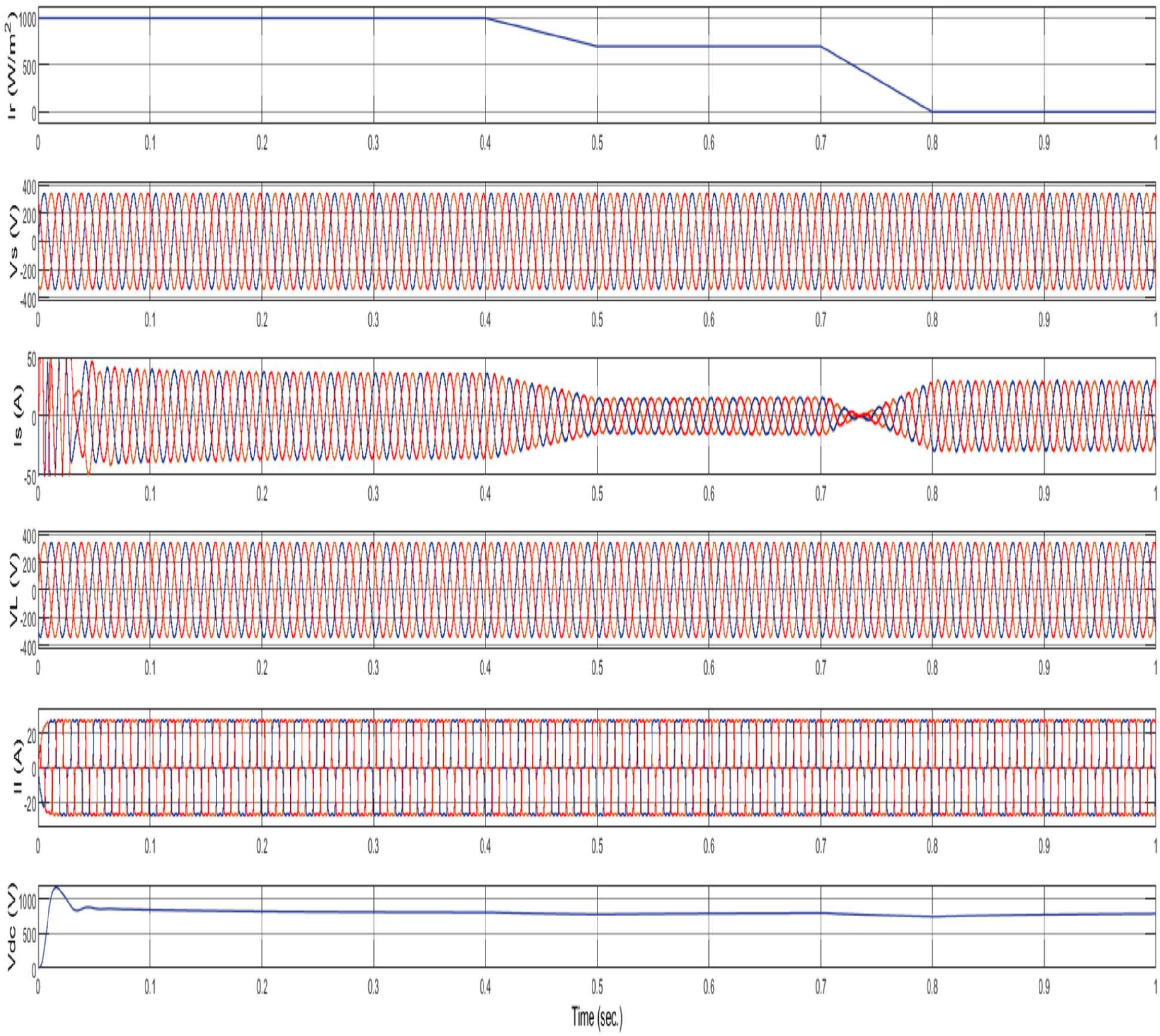

Fig. 4.22 Simulation results for grid tied inverter with non- linear load

Fig. 4.22 shows the grid voltage (Vs), grid current (Is), load voltage (Vl), load current (Il) and DC-link voltage (Vdc) waveforms of grid tied inverter connected to non-linear load. For 0 < t < 0.4s, the irradiance is $1000 W/m^2$, when this irradiance is reduced to $700 W/m^2$, the grid currents reduce and for 0.8s < t < 1s the irradiance is reduced to $0 W/m^2$. During this time interval the direction of grid currents reverses. The waveforms show that a constant DC link voltage is maintained at the PCC and also the load current successfully follows the voltage waveform and unity power factor operation is performed. The control technique is successfully implemented for non- linear power factor correction mode of operation.

4.20 SIMULINK MODEL BASED ON POWER BALANCE CONTROL TECHNIQUE OF GRID TIED INVERTER

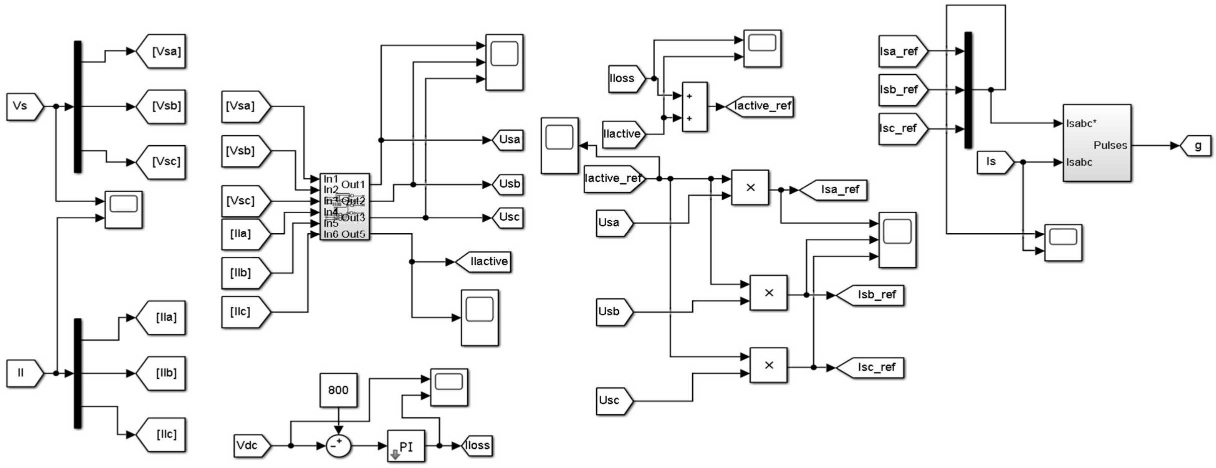

Fig. 4.23 Simulink model of POWER BALANCE control technique

Fig. 4.23 shows the simulink model of POWER BALANCE control theory. In this control technique, the grid voltage, load current, DC link voltage and the grid currents are used for the implementation of the inverter control. The unit templates are obtained using the instantaneous active power and the magnitude of the reference current waveform is determined by the loss component obtained using the DC link voltage.

4.21 SIMULINK MODEL OF GRID CONNECTED PV SYSTEM USING POWER BALANCE THEORY CONTROL, CONNECTED TO INDUCTIVE LOAD

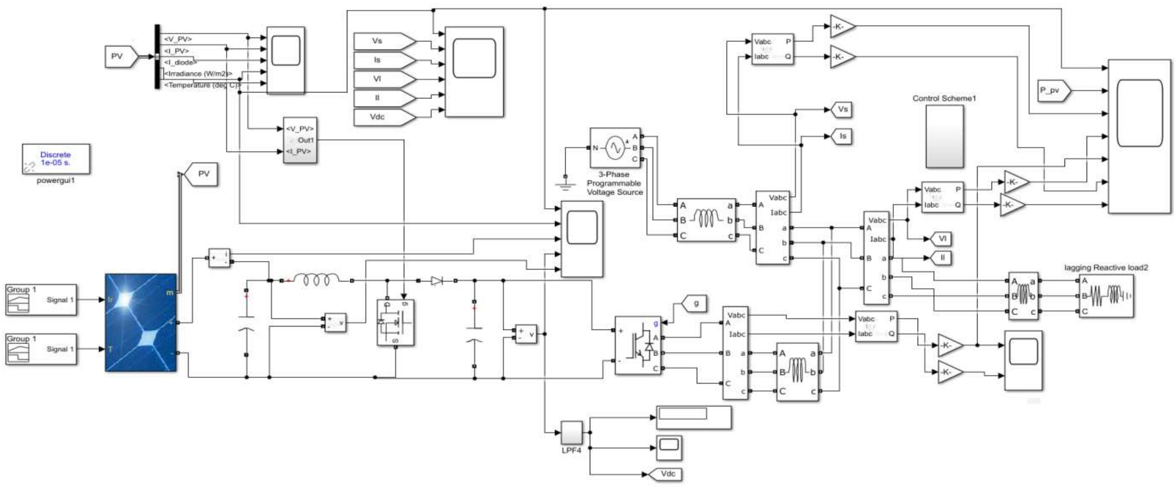

Fig. 4.24 Simulink model of grid connected PV system with POWER BALANCE THEORY based control of grid tied inverter and connected to R-L load

Fig. 4.24 shows the simulink model of complete grid tied PV system which consists of a PV array, Boost converter, MPPT control, inverter power circuit, inverter control, grid and the load. Voltage and current measurement blocks are used to measure the voltage and current waveforms in the system. An irradiance of 1000W/m^2 is used for $0 \leq t \leq 0.4$s which becomes 700W/m^2, for 0.5s < t < 0.7s and for 0.8s < t < 1s, the irradiance is reduced to 0W/m^2.

4.22 SIMULATION RESULTS OF GRID TIED INVERTER CONTROLLED USING PBT & FEEDING INDUCTIVE LOAD

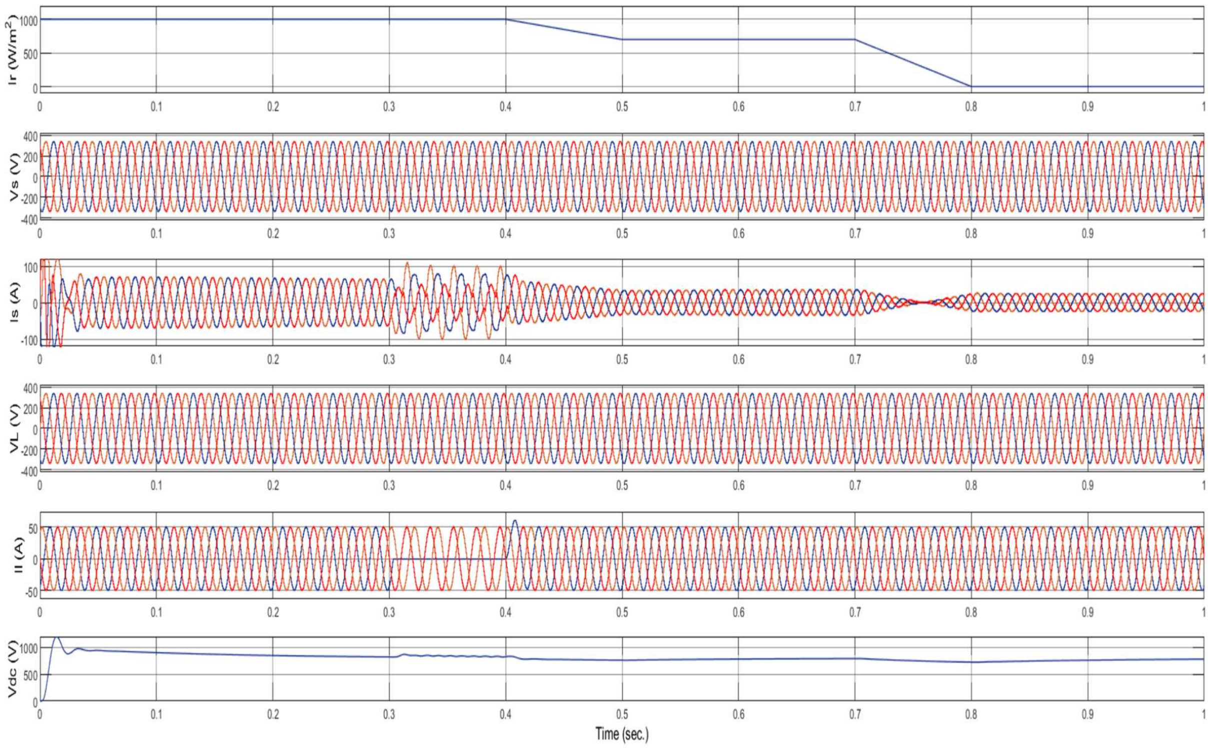

Fig. 4.25 Voltage and current waveforms for POWER BALANCE control of grid tied inverter connected to an R-L load

Fig. 4.25 Grid voltage (V_{sa}, V_{sb}, V_{sc}), grid current (I_{sa}, I_{sb}, I_{sc}), load voltage (V_{la}, V_{lb}, V_{lc}), load current (I_{sa}, I_{sb}, I_{sc}) and DC-link voltage (V_{dc}) waveforms in POWER BALANCE THEORY based control of grid tied inverter and connected to R-L load. A phase is switched off between t=0.3s to t=0.4s. An irradiance of 1000W/m^2 is provided to the grid during this time interval which is further reduced to 700W/m^2, for 0.5s < t < 0.7s. the grid currents reduces during this time span. The load voltage and current waveforms show that the load current successfully follows the voltage waveform and hence show unity power factor Also a constant DC link voltage is maintained The PBT control technique is successfully implemented for power factor correction mode of operation of grid tied inverter.

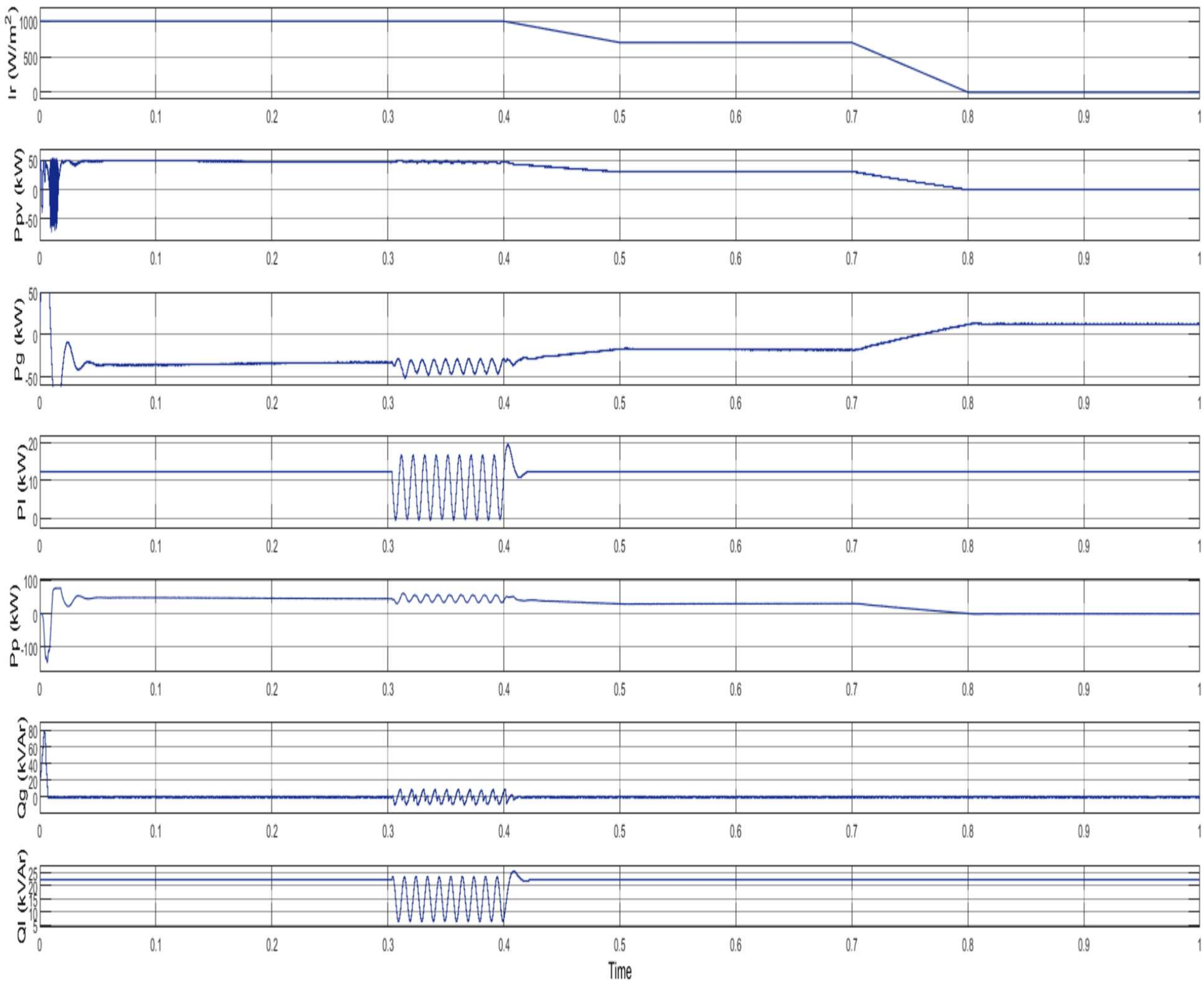

Fig. 4.26 Power flow in grid tied inverter control based on PBT

Fig. 4.26 shows the irradiance received by the PV array (Ir), power supplied by the PV array (Ppv), active power of the grid (Pg), active power of the load (Pl), reactive power of the grid (Qg), reactive power of the load (Ql) when the POWER BALANCE control technique is used for the control of grid tied inverter and it is connected to an R-L load. For $0 \leq t \leq 0.4$s, the active power supplied by the PV system is more than the active power required by the load, so the remaining active power is delivered to the grid. For time $0.5s < t < 0.7s$, when the irradiance is reduced to $700W/m^2$, the active power is still supplied to the load by the SPV array but less amount of excess power is supplied to the grid. For $0.8s < t < 1s$ the irradiance is reduced to $0W/m^2$. The active power produced by the PV array becomes equal to zero, so the active power required by the load is entirely supplied by the grid.

4.23 SIMULINK MODEL OF GRID CONNECTED PV SYSTEM USING POWER BALANCE THEORY CONTROL AND CONNECTED TO NON-LINEAR LOAD

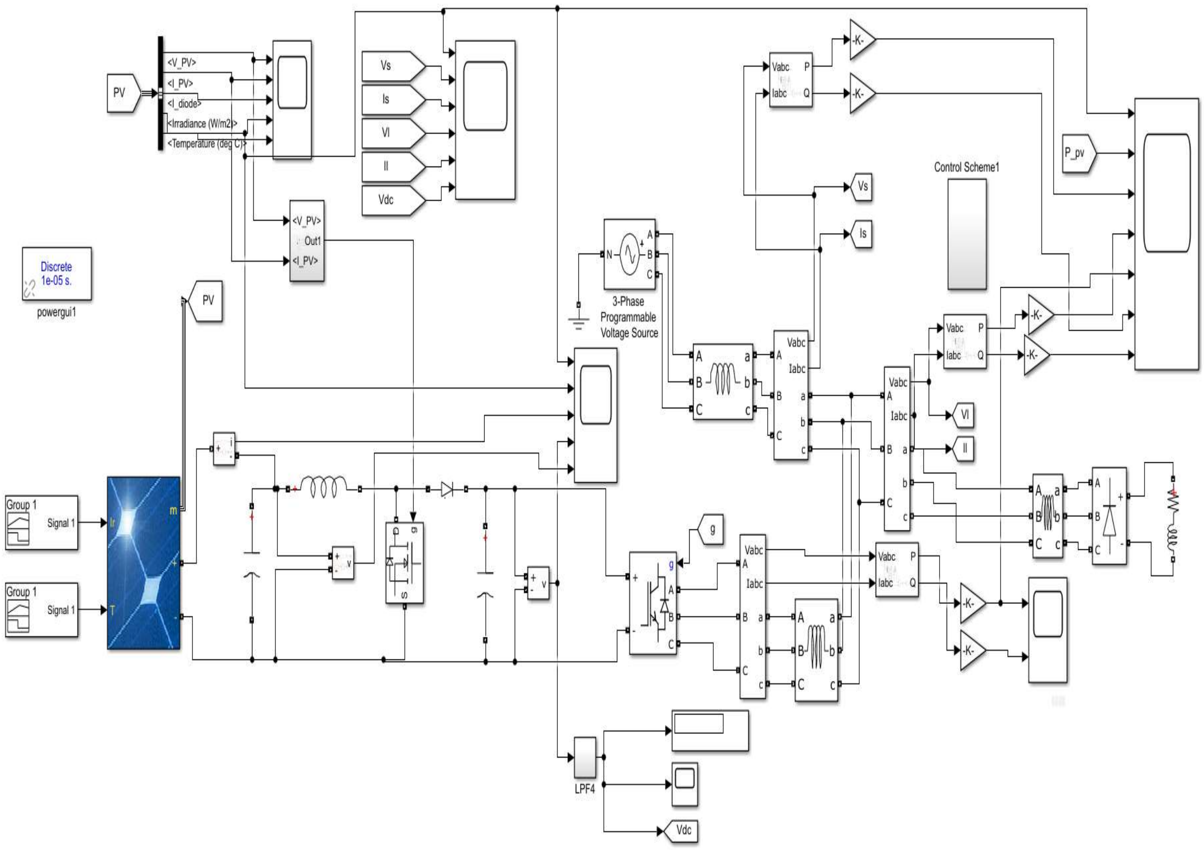

Fig. 4.27 Simulink model of grid integrated PV system with POWER BALANCE control of grid tied inverter connected to non- linear load

Fig. 4.27 shows the complete simulink model of a grid tied PV system with Power Balance control technique. Input temperature of the PV array is 25ºC and the irradiance is varied and is maintained at 3 different values. For time $0 < t < 0.4s$, irradiance is 1000W/m^2, for time $0.5s < t < 0.7s$ it is 700W/m^2 and for $0.8s < t < 1s$ irradiance is reduced to 0W/m^2.

4.24 SIMULATION RESULTS OF GRID TIED INVERTER WITH PBT BASED CONTROL SCHEME

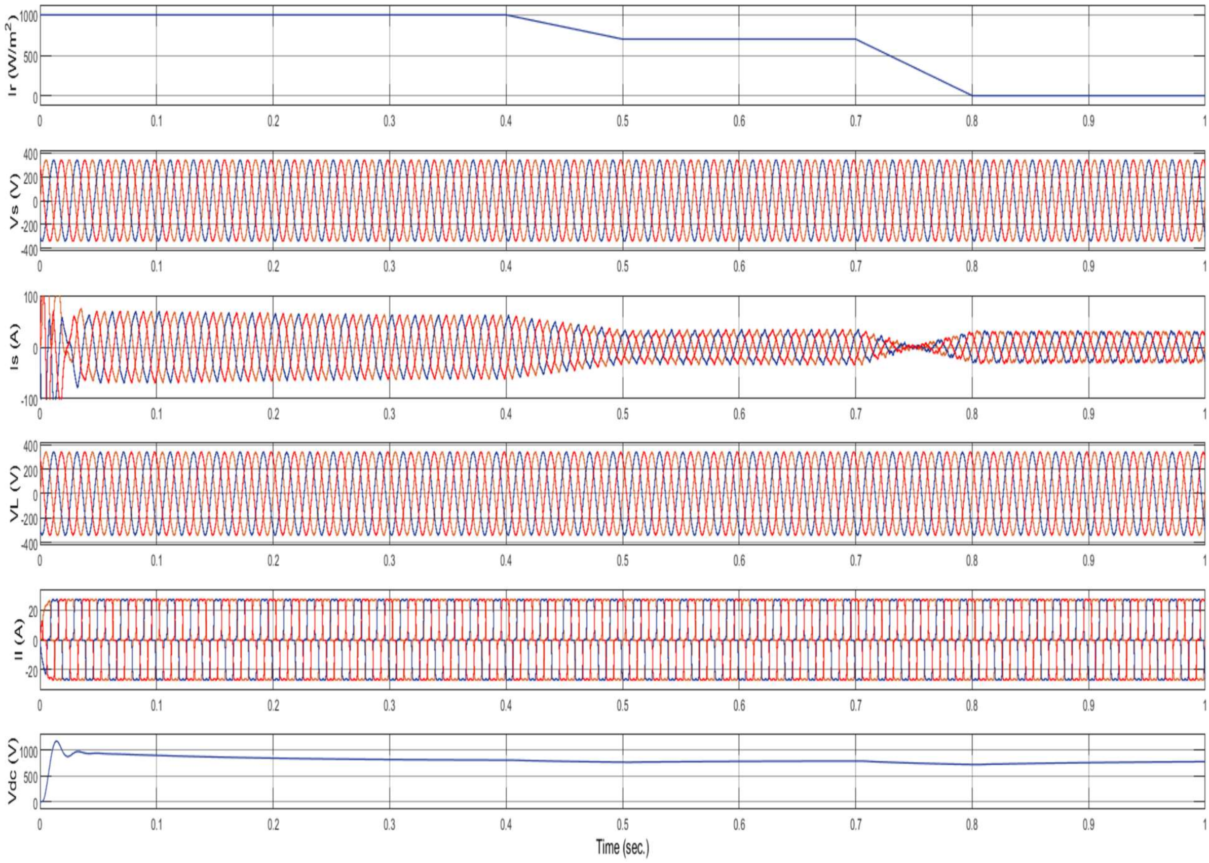

Fig.4.28 Simulation results of grid tied inverter with PBT control scheme

Fig. 4.28 shows the grid voltage (V_{sa}, V_{sb}, V_{sc}), grid current (I_{sa}, I_{sb}, I_{sc}), load voltage (V_{la}, V_{lb}, V_{lc}), load current (I_{sa}, I_{sb}, I_{sc}) and DC-link voltage (V_{dc}) waveforms in POWER BALANCE THEORY based control of grid tied inverter & connected to non-linear load. Irradiance received by the PV array is 1000W/m^2, for $0 < t < 0.4$s. the current flow is from the SPV array to the load and the grid. When the irradiance is reduced to 700W/m^2 for $0.5s < t < 0.7s$, less amount of current flows from PV array to the grid. For $0.8s < t < 1s$, the irradiance reduces to zero so the flow of current is from the grid to the non- linear load. The waveforms show that a constant DC link voltage is maintained. The load current successfully follows the voltage waveform and hence it shows unity power factor operation.

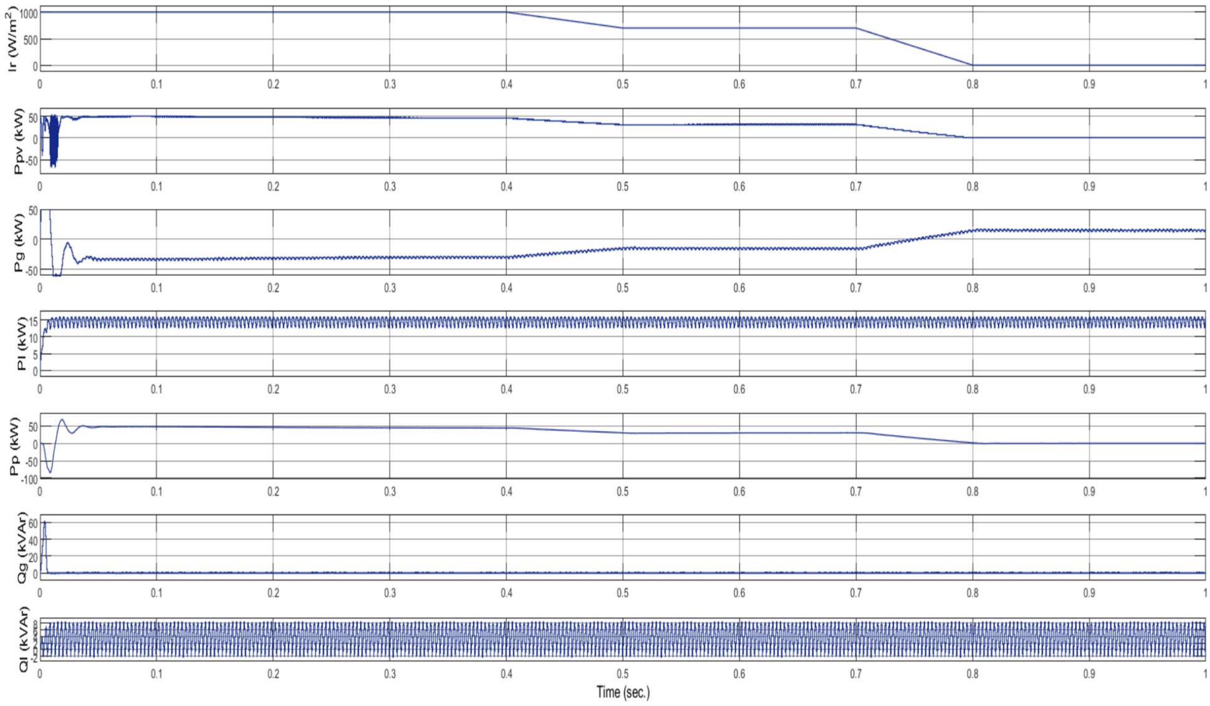

Fig. 4.29 Power flow in grid tied inverter connected to non- linear load & controlled using PBT

Fig. 4.29 shows the power supplied by the PV array, active power of the grid and load and reactive power of the grid and load when the inverter is controlled using the POWER BALANCE THEORY based control algorithm. As the control of the inverter is implemented in such a way that the reactive power is supplied by the PV system at all times, so the reactive power supplied by the grid is zero. For $0 \leq t \leq 0.4s$, the active power supplied by the PV system is more than the active power required by the load, so the remaining active power is supplied to the grid. For time $0.5s < t < 0.7s$, the irradiance is equal to $700W/m^2$. For $0.8s < t < 1s$, the irradiance is reduced to zero because of which the active power supplied by the PV system becomes zero so, the active power required by the load is entirely supplied by the grid.

4.25 COMPARISON OF PERFORMNCE OF GRIG TIED INVERTER CONTROL USING PI & PBT CONTROL SCHEMES

TABLE 4.5: COMPARISON BETWEEN PI AND PBT CONTROL BASED ON THD (%)

TYPE OF CONTROL TECHNIQUE	TYPE OF LOAD	GRID CURRENT THD (%)	LOAD CURRENT THD (%)	PCC VOLTAGE THD (%)
SIMPLE PI CONTROL	INDUCTIVE LOAD	1.87	0.08	0.09
	NON- LINEAR	2.17	22.93	0.09

	LOAD			
PBT CONTROL	INDUCTIVE LOAD	2.04	0.08	0.09
	NON- LINEAR LOAD	4.26	22.93	0.08

4.26 CONCLUSIONS

This chapter presents the modeling and simulation of the grid connected PV system using simple PI control and PBT based control of the VSC. It also presents the simulation of P&O MPPT control of PV array and its comparison along with the XSG based designing of P&O MPPT. It also contains the simulation of grid connected PV system using a simple PI control and using Power Balance Theory and their simulation results. The reactive power supplied by the grid is zero which implies that the reactive power demandedd by the load is supplied by the VSC and the power factor of the grid is maintained at unity.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE OF WORK

5.1 MAIN CONCLUSIONS

A grid integrated 50kW SPV system is implemented in MATLAB/ Simulink. The P&O technique of MPPT is modeled & simulated to extract the maximum power from the PV array at any given point of time . A simulink model of the P and O MPPT is used in this analysis. The Xilinx System Generator based model of the MPPT is also developed.

For the inverter control two types of control techniques are used:

1) A simple PI based control technique
2) Power Balance Theory

In both the control techniques a reference grid current waveform is generated & compared to actual grid current to generate PWM control of VSI.

In simple PI based control technique load voltage, and DC link voltage are used to generate the reference current waveform whereas, in the POWER BALANCE THEORY, the grid voltage, load current and the DC link voltage are used in order to generate the reference currents. The reference current waveform is compared with the grid currents and this difference in the two waveforms is used to generate the gate pulses which are given to the inverter. The system operates at unity power factor as the grid current waveform follows the voltage waveform. Hence both control algorithms are successfully implemented for power factor correction mode and active/ reactive power exchange with grid.

5.2 FUTURE SCOPE

A grid integration of a PV system is a need of the hour. As with time our conventional sources of energy are depleting, we need to focus over the non- conventional resources of energy. These non- conventional resources of energy are present in the nature in abundance and right kind of technology can fully utilize them and make their efficient use. As the technology is advancing, the number of controllers to control these systems are also increasing. The commercial PV panels are only 15-20% efficient. The efficiency of PV array can be increased to many folds with the right technology. Also, the various other advance control algorithms can be used for the control of the inverters. The FPGA based control of these inverters will enhance the efficiency of the system along with increasing their reliability. The FPGA are capable of performing complex processing in rea time and execute faster than software code running on general purpose CPU.

REFERENCES

[1] R. M. Elavarasan *et al.*, "A Comprehensive Review on Renewable Energy Development, Challenges, and Policies of Leading Indian States With an International Perspective," in *IEEE Access*, vol. 8, pp. 74432-74457, 2020.

[2] Installed RE capacity in Indian states as of 29 February 2020. Available online: https://mnre.gov.in/the-ministry/physical-progress (accessed on 21 March 2020).

[3] Ashwani Kumar, Kapil Kumar, Naresh Kaushik, Satyawati Sharma, Saroj Mishra, "Renewable energy in India: Current status and future potentials", *Renewable and Sustainable Energy Reviews*, Volume 14, Issue 8, 2010, Pages 2434-2442, ISSN 1364-0321, doi:10.1016/j.rser.2010.04.003.

[4] G.Sargsyan, M. Bhatia, S.G.Banerjee, K. Raghunathan, R. Soni, "Unleashing the potential of renewable energy in India", The World Bank Group, pp.54, 2011

[5] Swami Prakash Srivastava Surat Prakash Srivastava, "SOLAR ENERGY AND ITS FUTURE ROLE IN INDIAN ECONOMY", in *International Journal of Environmental Science: Development and Monitoring (IJESDM)*, ISSN No. 2231-1289, Volume 4 No. 3 (2013)

[6] S. Manish, Indu R. Pillai, Rangan Banerjee, "Sustainability analysis of renewables for climate change mitigation", Energy for Sustainable Development, Volume 10, Issue 4, 2006, Pages 25-36, ISSN 0973-0826, doi:10.1016/S0973-0826(08)60553-0.

[7] Rabl, Ari & Spadaro, Joseph. (2016), "External Costs of Energy: How Much is Clean Energy Worth?" „*Journal of Solar Energy Engineering*. 138. 10.1115/1.4033596.

[8] Rathore, Pushpendra & Chauhan, Durg & Singh, Rudra. (2018), "Decentralized solar rooftop photovoltaic in India: On the path of sustainable energy security", *Renewable Energy*. 131. 10.1016/j.renene.2018.07.049.

[9] Wayan G. Santika, M. Anisuzzaman, Parisa A. Bahri, G.M. Shafiullah, Gloria V. Rupf, Tania Urmee, "From goals to joules: A quantitative approach of interlinkages between energy and the Sustainable Development Goals", Energy Research & Social Science, Volume 50, 2019, Pages 201-214, ISSN 2214-6296, doi:10.1016/j.erss.2018.11.016.

[10] Patel, Beena & Gami, Bharat & Baria, Vipul & Patel, Akash & Patel, Pankaj. (2018), "Co-Generation of Solar Electricity and Agriculture Produce by Photovoltaic and Photosynthesis—Dual Model by Abellon, India", *Journal of Solar Energy Engineering*, 141. 10.1115/1.4041899.

[11] Ibrahem S. Altarawneh, Saleh I. Rawadieh, Muafag S. Tarawneh, Sultan M. Alrowwad, and Firas Rimawi, "Optimal tilt angle trajectory for maximizing solar energy potential in Ma'an area in Jordan", in *JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY* 8, 033701 (2016)

[12] Dhiraj Magare, Oruganti Sastry, Rajesh Gupta,Birinchi Bora, Yogesh Singh, Humaid Mohammed, "Wind effect modeling and analysis for estimation of photovoltaic module temperature", in *Journal of Solar Energy Engineering*. Received May 14, 2017; Accepted manuscript posted November 29, 2017.

[13] Mr. Dharmendra kumar Singh, Mr. Mahendra Kumar Pradhan, "Design and Simulation of Photovoltaic System in Matlab using Simulink*", International Journal on Future Revolution in Computer Science & Communication Engineering* Volume: 4 Issue: 4

[14] C.Jena, Amruta Das, C.K.Panigrahi, M.Basu,"Modelling and Simulation of Photovoltaic Module with Buck-Boost Converter" *International Journal of Advanced Engineering and Nano Technology (IJAENT)* ISSN: 2347-6389, Volume-1, Issue-3, February 2014

[15] M. Abdulkadir, A. S. Samosir and A. H. M. Yatim,"MODELING AND SIMULATION BASED APPROACH OF PHOTOVOLTAIC SYSTEM IN SIMULINK MODEL" *ARPN Journal of Engineering and Applied Sciences*, VOL. 7, NO. 5, MAY 2012

[16] N. Pandiarajan and R. Muthu, "Mathematical modeling of photovoltaic module with Simulink," 2011 *1st International Conference on Electrical Energy Systems*, Newport Beach, CA, 2011, pp. 258-263.

[17] Kinal Kachhiya, Makarand Lokhande, Mukesh Patel, "MATLAB/Simulink Model of Solar PV Module and MPPT Algorithm", *National Conference on Recent Trends in Engineering & Technology*, 13-14 May 2011.

[18] Samer Said1, Ahmed Massoud1, Mohieddine Benammar1 and Shehab Ahmed2, "A Matlab/Simulink-Based Photovoltaic Array Model Employing SimPowerSystems Toolbox", *Journal of Energy and Power Engineering* 6 (2012) 1965-1975.

[19] Kamal Keshavani, Jigar Joshi, Vishrut Trivedi, Mitesh Bhavsar, "Modelling and Simulation of Photovoltaic Array Using Matlab/Simulink" 2014 *IJEDR* Volume 2, Issue 4 ISSN: 2321-9939.

[20] Singh, Omveer & Rajput, Saurabh. (2016), "Mathematical modelling and simulation of solar photovoltaic array system", *International Conference on Research Advances in Integrated Navigation Systems (RAINS)*, 1-5.

[21] Xuan Hieu Nguyen1, Minh Phuong Nguyen,"Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink", Nguyen and Nguyen Environ Syst Res (2015) 4:24 DOI 10.1186/s40068-015-0047-9

[22] M. G. Villalva, J. R. Gazoli and E. R. Filho, "Modeling and circuit-based simulation of photovoltaic arrays," *2009 Brazilian Power Electronics Conference*, Bonito-Mato Grosso do Sul, 2009, pp. 1244-1254.

[23] Intissar Mousa, Adel Khedher, " Photovoltaic emulator based on PV simulator RT implementation using XSG tools for an FPGA control: Theory and explanation", *International Transactions on Electrical Energy SystemsVolume* , 29, Issue 8.

[24] S. Chowdhury, S. P. Chowdhury, G. A. Taylor and Y. H. Song, "Mathematical Modelling and Performance Evaluation of a Stand-Alone Polycrystalline PV Plant with MPPT Facility," *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Pittsburgh, PA, 2008, pp. 1-7.

[25] H. AbdEl-Gawad and V. K. Sood, "Overview of connection topologies for grid-connected PV systems," *2014 IEEE 27th Canadian Conference on Electrical and Computer Engineering (CCECE)*, Toronto, ON, 2014, pp. 1-8.

[26] Vipra Joshi,Pushpinder kaur, " GRID CONNECTED PV SYSTEM USING MPPT" *International Journal of Scientific & Engineering Research*, Volume 6, Issue 5, May-2015 ISSN 2229-5518

[27] Roberto Faranda, Sonia Leva, "Energy comparison of MPPT techniques for PV Systems", *WSEAS TRANSACTIONS on POWER SYSTEMS*, ISSN: 1790-5060, Issue 6, Volume 3, June 2008.

[28] S.Jotheeswari, T.S.Anandhi, "DEVELOPMENT OF VHDL CODING FOR MAXIMUM POWER POINT TRACKING ALGORITHMS", *International Journal Of Current Engineering And Scientific Research (Ijcesr)*, ISSN (PRINT): 2393-8374, (ONLINE): 2394-0697, VOLUME-3, ISSUE-7, 2016 49.

[29] Paul, Abhishek & Dey, Bijit & Mandal, Nirabhra & Bhattacharjee, Ankur. (2016), "MATLAB/Simulink model of stand-alone Solar PV system with MPPT enabled optimized Power conditioning unit", 1-6.

[30] Mohd Ilyas, Shamshad Ali, Mumtaz Ahmad Khan, "Modeling and Simulation of 10 kW Grid Connected PV Generation System Using Matlab/Simulink", *International Journal of Applied Engineering Research*, ISSN 0973-4562 Volume 13, Number 24 (2018) pp. 16962-16970.

[31] Mr. M.Rupesh, Dr. Vishwanath Shivalingappa, "Comparative analysis of P&O and incremental conductance method for PV system", *International Journal of Engineering & Technology*, 7 (3.29) (2018) 519-523.

[32] Anuradha, Satish Kumar, "Study and Comparison of Various MPPT Algorithms in Solar Power System", *International Journal of Innovative Science, Engineering & Technology*, Vol. 2 Issue 12, December 2015

[33] Sandeep Neupane, Ajay Kumar, "Modeling and Simulation of PV array in Matlab/Simulink for comparison of perturb and observe & incremental conductance algorithms using buck converter", *International Research Journal of Engineering and Technology* (IRJET), Volume: 04 Issue: 07 | July -2017, e-ISSN: 2395-0056, p-ISSN: 2395-0072

[34] D. Sera, L. Mathe, T. Kerekes, S. V. Spataru and R. Teodorescu, "On the Perturb-and-Observe and Incremental Conductance MPPT Methods for PV Systems," in *IEEE Journal of Photovoltaics*, vol. 3, no. 3, pp. 1070-1078, July 2013.

[35] M.Lokanadham, K. Vijaya Bhaskar, “Incremental Conductance Based Maximum Power Point Tracking (MPPT) for Photovoltaic System”, *International Journal of Engineering Research and Applications (IJERA)*, ISSN: 2248-9622, Vol. 2, Issue 2,Mar-Apr 2012, pp.1420-1424

[36] Ratna Ika Putria, Sapto Wibowob, Muhamad Rifa, “Maximum power point tracking for photovoltaic using incremental conductance method”, 2nd International Conference on *Sustainable Energy Engineering and Application, ICSEEA* 2014.

[37] P. Rajesh, S. Rajasekar, R. Gupta and P. Samuel, "Solar array system simulation using FPGA with hardware co-simulation," 2014 *IEEE 23rd International Symposium on Industrial Electronics (ISIE), Istanbul*, 2014, pp. 2291-2296.

[38] Nadjwa Chettibi, Adel Mellit, “Study on Control of Hybrid Photovoltaic-Wind Power System Using Xilinx System Generator”, R.-E. Precup et al. (eds.), *Solar Photovoltaic Power Plants, Power Systems*.

[39] Koca, Yavuz & Aslan, Yılmaz & Yonetken, Ahmet & Oğuz, Yüksel. (2019), “Boost Converter Design and Analysis for Photovoltaic Systems”, 4th International Conference on *Engineering Technology and Applied Sciences (ICETAS)*, April 24-28 2019 Kiev Ukraine

[40] Geetha S Nair, Dr. Bisharathu Beevi, “TWO-STAGE GRID CONNECTED PHOTOVOLTAIC SYSTEM WITH UPQC APPLIED TO AC MICROGRIDS”, *International Journal Of Engineering Sciences & Research Technology*, ISSN: 2277-9655, Impact Factor: 5.164, CODEN: IJESS7.

[41] S. Khan, B. Singh and P. Makhija, "A review on power quality problems and its improvement techniques," 2017 *Innovations in Power and Advanced Computing Technologies (i-PACT)*, Vellore, 2017, pp. 1-7.

[42] W. E. Reid, "Power quality issues-standards and guidelines," Proceedings of IEEE Pulp and Paper Industry Conference, Nashville, TN, USA, 1994, pp. 108-115

[43] E. Hossain, M. R. Tür, S. Padmanaban, S. Ay and I. Khan, "Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices," in IEEE Access, vol. 6, pp. 16816-16833, 2018.

[44] Sung-Hun Ko, S. R. Lee, H. Dehbonei and C. V. Nayar, "Application of voltage- and current-controlled voltage source inverters for distributed generation systems," in *IEEE Transactions on Energy Conversion*, vol. 21, no. 3, pp. 782-792, Sept. 2006.

[45] B. Singh, D. T. Shahani and A. K. Verma, "Power balance theory based control of grid interfaced solar photovoltaic power generating system with improved power quality," *2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Bengaluru, 2012, pp. 1-7.

[46] Jampana, Bangarraju & Rajagopal, Veeramalla & Laxmi, A.J.. (2016), "Power quality enhancement using power balance theory based DSTATCOM", *Advances in Electrical and Electronic Engineering*.

[47] S. Golestan, M. Monfared and F. D. Freijedo, "Design-Oriented Study of Advanced Synchronous Reference Frame Phase-Locked Loops," in *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 765-778, Feb. 2013.

[48] B. Singh, M. Kandpal and I. Hussain, "Control of Grid Tied Smart PV-DSTATCOM System Using an Adaptive Technique," in *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 3986-3993, Sept. 2018.

[49] S. Zhou, J. Liu, L. Zhou and H. She, "Cross-coupling and decoupling techniques in the current control of grid-connected voltage source converter," 2015 *IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 2821-2827.

[50] Bhim Singh, D. T. Shahani, Arun Kumar Verma, "IRPT Based Control of a 50 kW Grid Interfaced Solar Photovoltaic Power Generating System with Power Quality Improvement", 2013 4th *IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, July 2013.

[51] Bhim Singh, Chinmay Jain, Sagar Goel, Rahul Gogia & Umashankar Subramaniam (2016), "A Sustainable Solar Photovoltaic Energy System Interfaced with Grid-Tied Voltage Source Converter for Power Quality Improvement", *Electric Power Components and Systems,* Vol. 0 (2017), No. 0.

[52] Tripathi, Ravi & Singh, Alka (2013), "SRF Theory Based Grid Interconnected Solar Photovoltaic (SPV) System with Improved Power Quality", *IEEE International conference on Communication, Control, Signal processing and Computing application (C2SPCA)*.