MODELING AND SIMULATION OF THREE PHASE GRID CONNECTED SOLAR PHOTOVOLTAIC SYSTEM WITH POWER QUALITY ANALYSIS

DISSERTATION

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CERTIFICATE

I, **Shivam Gupta**, Roll No. 2K14/PSY/18 student of **M. Tech. (Power System)**, hereby declare that the dissertation titled "Modeling and Simulation of Three Phase Grid Connected Solar Photovoltaic System with Power Quality Analysis" under the supervision of Dr. M. Rizwan, Assistant Professor, Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology. This dissertation has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

In modern contest the world is moving from conventional energy sources to the renewable one. It is due to it greater abundance and environment friendly characteristics. Solar energy is one of the most promising renewable resources that can be used to produce electric energy through photovoltaic process. A significant advantage of photovoltaic (PV) systems is the use of the abundant and free energy from the sun.

Power electronic devices used as interface between renewable power and its user. It makes the power generated by renewable sources suitable for utilization. Solar power contribution in power generation has been increasing very fast and cost of power generated by solar photovoltaic is falling rapidly. Solar photovoltaic cell converts solar energy directly into dc power. Power is mostly transmitted and utilized in ac form because of advantages associated with it. To convert the dc power into ac, a highly efficient converter is required for optimum utilization of energy.

The MPPT algorithm uses the I_{PV} and V_{PV} of the PV array and gives the MPP and a V_{DCREF}. This voltage is then passed on to the inverter and then further to the three-phase grid. In this thesis the behaviour of the active and reactive power of the grid which is supplied by the PV array is investigated. The various currents such as inverter current, grid current and load currents are also investigated.

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ABBREVIATIONS AND LIST OF SYMBOLS

AC	Alternating Current
DC	Direct Current
GHG	Green House Gas
I&C	Incremental Conductance
I_{MPP}	Current at Maximum Power Point
Isc	Short Circuit Current
MIC	Module Integrated Converter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PV	Photovoltaic
RES	Renewable Energy Sources
SPV	Solar Photovoltaic
SOC	State of Charge
THD	Total Harmonic Distortion
Voc	Open circuit Voltage
V_{MPP}	Voltage at Maximum Power Point
µH	Micro Henry
µF	Micro Farad
Ω	ohm

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The purpose of this chapter is to present the motivation behind the work done in this dissertation. The chapter also provides the main objectives of the research as well as the dissertation organization. There are different sources of energy existing in this world. These sources are categorises mainly into two groups.

i) Renewable(that don't get exhausted and replenished on its own)
ii) Non-renewable(a source that requires a large amount of time)

Renewable & non-renewable energy sources produces secondary energy sources such as electricity and hydrogen etc. Renewable energy sources included following:

a) Solar energy (energy from Sun converted into electricity & heat)
b) Wind energy
c) Biomass energy
d) Geo-thermal energy (from inside the earth)
e) Hydropower etc.

However, in the present scenario most of the energy requirement are fulfilled by conventional or non-renewable energy sources. These are formed over a prolonged period of time under high pressure & temperature inside the earth's crust, hence are called fossil fuels. These sources includes the following:

a) Coal
b) Oil
c) Natural gas
d) Uranium

The increased concerns over the climate changes and other environmental impact due to the extreme dependence on fossil fuel have led to the proliferation of renewable energy sources like wind and solar photovoltaic power across the globe. Solar PV energy source, which currently ranks third among the most deployed renewable energy sources in the world, after hydro and wind power.

1.2 MOTIVATION

The demand for electric energy is expected to increase globally due to the rapid population growth and industrialization. This rapid increase in the energy demand requires electric utilities to increase their generation. In the last six decades, India's energy use has increased 16 times and the installed energy capacity by 84 times, still India is facing the problem of acute power deficit. The present scenario indicates that India's future energy requirements are going to be extremely high. In order to meet the ever increasing power requirements, huge amount of power needs to be generated in the existing power sector. According to Ministry of Power statistics, the installed power generation capacity of India as on May 31, 2016 was 303083 MW. Further, the total demand for electricity in India is expected to cross 950,000 MW by 2030 and it is beyond doubt that a substantial contribution would be from renewable energy.

As on 31st May 2016, the current installed capacity of thermal power is 211670 MW which is 69.84% of total installed capacity. Current installed capacity of coal based thermal power is 186242 MW which comes to 61.45% of total installed base and current installed base of gas based thermal power is 24508 MW which is 8% of total installed base, while oil based thermal power is 1,200 MW which is 0.4% of total installed base. In addition, 42783 MW of power is generated through large hydro and 5780 MW and 42849 MW of power is generated from nuclear energy and renewable energy resources respectively. The graphical representation of Indian power sector as on May 31, 2016 is presented in Figure 1.1.

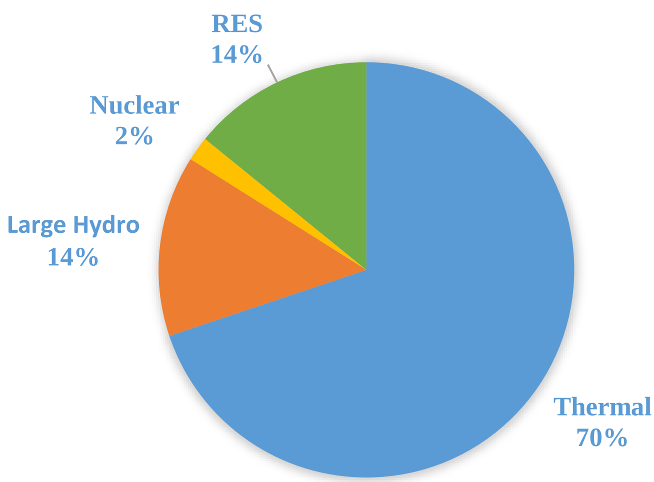


Figure 1.1 Indian Power Sector at Glance

As renewable energy is concerned, the current installed base of renewable energy is 42849 MW. The power generation through wind is 26866 MW, small hydro contributes 4273 MW while the power generated from biomass and solar photovoltaic technology is 4946 MW and 6762 MW respectively. The potential of above mentioned resources is huge and this could be sufficient to meet the future requirements of power in the country. The graphical representation of contribution of renewable energy resources in Indian power sector as on 31st May, 2016 is shown in Figure 1.2.

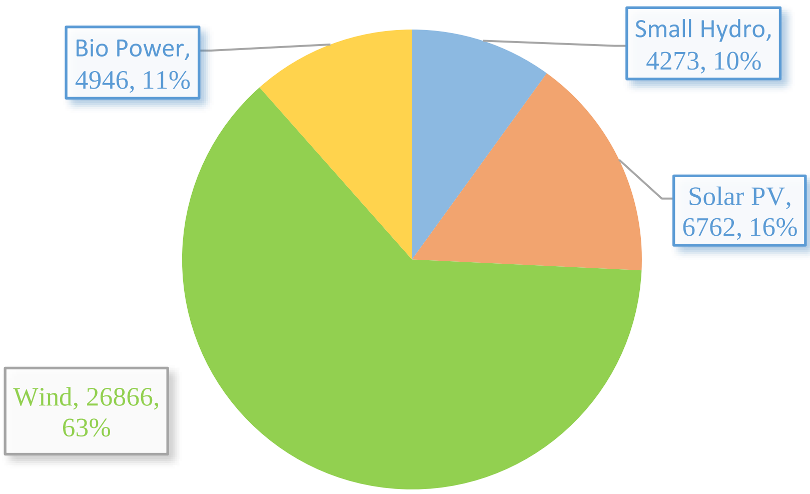


Figure 1.2 Contribution of RES in Indian Power Sector

However, the increasing use of fossil fuels accounts for a significant portion of environmental pollution and greenhouse gas emissions, which are considered the main reason behind the global warming. Solar energy as an energy source has a large theoretical potential, and can be utilized both directly and indirectly. Among various types of renewable energy sources (RES), solar energy and wind energy have become the most promising and attractive because of advancement in power electronic technique. Photovoltaic (PV) sources are used nowadays in many applications as they own the advantage of being maintenance and pollution free. In the past few years, solar energy sources demand has grown consistently due to the following factors:

1) Increasing efficiency of solar cells.
2) Manufacturing technology improvement.
3) Economies of scale.

Meanwhile, more and more PV modules have been and will be connected to utility grid in many countries. Now the largest PV power plant is more than 100MW all over the world. Furthermore, the output of PV arrays is influenced by solar irradiation and weather conditions. PV systems are usually used in three main fields:

1) Satellite applications, where the solar arrays provide power to satellites.

2) Off-grid applications, where solar arrays are used to power remote loads that are not connected to the electric grid.

3) On-grid or grid connected applications, in which solar arrays are used to supply energy to grid.

Grid-connected PV systems can be installed on the facades and rooftops of buildings, on the shades of parking lots. They can also be installed as power plants that aim to inject all their produced power into the grid. PV penetration levels in the Indian electricity grids are still very low. However, the Ministry of New and Renewable Energy (MNRE) is targeting to add 20,000 MW grid connected solar power by 2017 under Jawaharlal Nehru National Solar Mission (JNNSM). India's national solar power capacity target has been quoted as 100 GW by 2022, mostly on the basis of speeches from ministers and high level bureaucrats. This will change the scenario significantly.

India sets a year on year target to achieve ambitious 100 GW target according to bloomberg new energy finance; The Economic Times which is shown in the Figure 1.3.

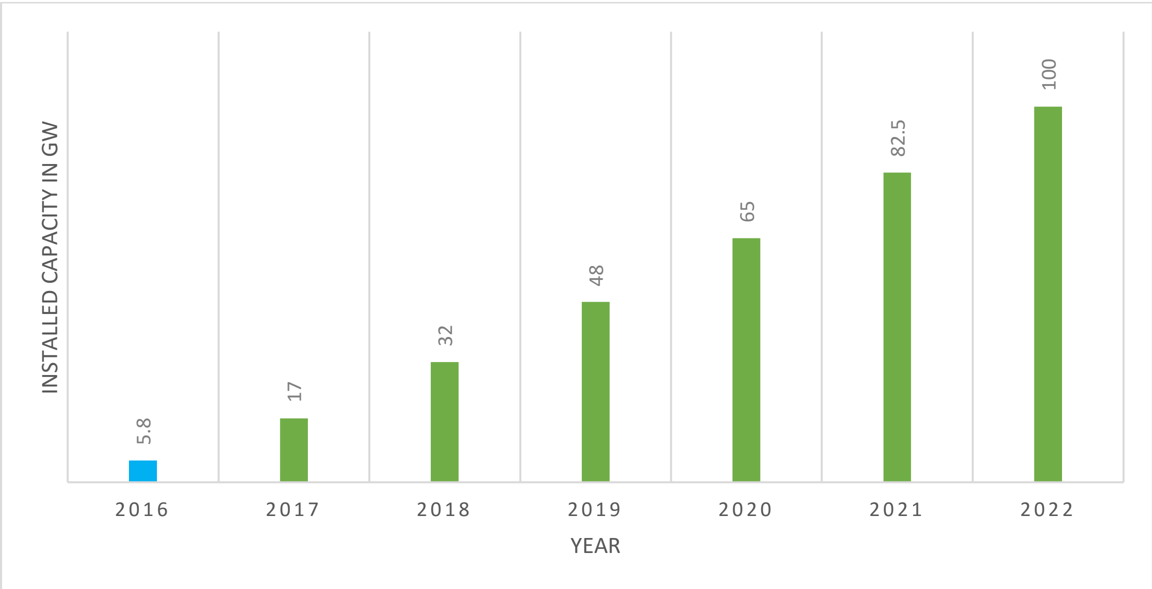


Figure 1.3 Targeted Installed Capacity of Solar PV (Cumulative)

Penetration of solar energy is increasing rapidly over the last decade due to its availability and climate-friendly attributes. Solar energy is free from greenhouse gas (GHG) emission and plays a key role in developing a sustainable power system for the future. However, the intermittent nature of solar energy creates a number of potential challenges in integrating large-scale photovoltaic (PV) with the grid. Voltage fluctuation, voltage management, harmonic distortion, demand management, and load rejection are the major potential issues concerning the application of photovoltaic in Single Wire networks. Of particular interest was the adverse effect on voltage instability of the network with varying PV penetration. Studies shows that voltage rises across the network would exceed regulatory standards with the high penetration of PV in networks.

1.3 SCOPE OF WORK

The increased concerns over the climate changes and other environmental impact due to the extreme dependence on fossil fuel have led to the proliferation of renewable energy sources like solar photovoltaic power across the globe. Solar PV is a sustainable energy source, which currently ranks third among the most deployed renewable energy sources in the world, after hydro and wind power. AC modules are considered as the new face of PV power and it employs a commercial PV module together with an inverter. The composite system is more flexible, easier to handle and feeds power directly into the utility grid. The power output of an AC module must meet the utility requirements in power quality. Grid synchronization is another major concern for grid-connected systems requiring the grid variables to be monitored continuously. . The objective of this thesis is

- To design and develop MATLAB/Simulink model of Solar PV system.
- To develop the MATLAB simulation model of three phase solar PV system with low voltage grid integration with various control schemes.
- Analyse the performance of parameters of grid such as voltage, current and power as the percentage penetration of solar PV increases.

1.4 ORGANISATION OF THESIS

CHAPTER 1: INTRODUCTION

In this chapter introduction to India’s power sector scenario, introduction to solar energy and scope of this dissertation is discussed.

CHAPTER 2: LITERATURE REVIEW

This chapter consists of the literature survey on Solar PV technologies, DC/DC converter, MPPT techniques, PWM inverter, and three phase grid connected PV systems.

CHAPTER 3: SOLAR PV TECHNOLOGY: AN OVERVIEW

This chapter deals with the theoretical information regarding the use of solar PV technology.

CHAPTER 4: CONTROL STRATERGIES FOR SOLAR PV SYSTEM

This chapter describes the detailed design and modeling of standalone solar PV system for battery bank charging with simulation results. This chapter also consists the performance analysis of various MPPT algorithms.

CHAPTER 5: DESIGN & MODELING OF THREE PHASE GRID CONNECTED SOLAR PV SYSTEM

This chapter presents design, modeling and simulation of a three phase grid connected PV system with various control schemes.

CHAPTER 6: RESULTS & DISSCUSIONS

This chapter presents result and discussions.

CHAPTER 7: CONCLUSION & FUTURE SCOPE

This chapter brings out the main conclusion of this dissertation and suggest for scope of further works.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter consists of a literature survey on various modules in this project. Various books and research paper related to Solar PV technology, MPPT algorithms, DC/DC converters, and grid connected PV inverter topologies, power quality issues with grid connected PV systems have been studied, which form the back bone of the thesis.

2.2 SOLAR PHOTOVOLTAIC TECHNOLOGY

India is blessed a vast solar energy potential, which is about 5000 trillion kWh/year (MNRE). Out of which we are able to exploit the small amount of power i.e. 6762 MW as on 31st May 2016.

Three major families of PV cells are monocrystalline technology, polycrystalline technology and thin film based technologies. The monocrystalline and polycrystalline technologies are based on microelectronic manufacturing technology and their efficiency is in general between 10% and 15% for monocrystalline and between 9% and 12% for polycrystalline. For thin film cells, the efficiency is 10% for a-Si, 12% for CuInSe2 and 9% for Cd-Te. The monocrystalline cell has the highest efficiency.

2.3 MODELING, DESIGN AND SIMULATION OF PV ARRAY

A circuit model of PV cell is necessary in order to study the photovoltaic system. Output parameters of solar cell depend upon the meteorological parameters like solar irradiance and temperature etc. The output power produced by solar cell is not sufficient for use. So the solar cells are grouped together to make panels and arrays.

Natrajan Pandiarajan et.al [1] presented circuit model of photovoltaic module for a common use of material scientists and power electronic circuit designers for developing the better PV power plans. The authors presented the detailed modeling procedure for the circuit model with equations using sim power system block of MATLAB/ Simulink. This paper also presented the MPPT control with DC/DC boost converter with appropriate simulation results.

M. Abdulkadir et.al [3] proposed a user friendly model using Simulink. Authors accounted the effect of varying irradiance and temperature on the developed model. They verified the proposed model with practical model of 36W PV module.

Samer Said et.al [4] considers the PV cell as the main building block for simulation and monitoring the performance of PV array. The proposed model simulated for various temperature & isolation values and P-V, I-V characteristics obtained for different parameters. The authors also studied different patterns of partial shading on PV arrays. This paper describes a model of PV array which is suitable to simulate the dynamic performance of PV base power generating systems.

$$I = N_p I_{PH} - N_p I_s \left[\exp\left\{\frac{qV}{N_s AkT}\right\} - 1\right] \tag{2.1}$$

By-pass diode significantly affects the output characteristics of PV array in case of shading. Authors simulate the presented model for comparing the shaded and unshaded PV array characteristics. This study consists of two major sections; one is under uniform insolation and another is under partial shaded conditions. Presented results conclude that presence of multiple peaks (local peaks) reduces the MPPT efficiency because it fails to observe the global peak.

Kashif Ishaque et.al [5] presented a two diode model of PV cell. The proposed model gives better accuracy at low values of solar irradiance and allows predicting solar PV system performance more accurately. Authors estimate the values of Rp and Rs so that the input parameter can be reduced to four and hence computational time can be reduced. A standard PV module datasheet is used as information to PV simulator. Large array simulation is supported by the simulator and that can be interface with different power converter & MPPT algorithms. Model accuracy verified by using five different modules from various manufacturers.

Output current equation of two diode model PV cell is given as

$$I = I_{PV} - I_{o1}\left[\exp\left\{\frac{V+IR_s}{\alpha_1 V_{T1}}\right\} - 1\right] - I_{o2}\left[\exp\left\{\frac{V+IR_s}{\alpha_2 V_{T2}}\right\} - 1\right] - \left\{\frac{V+IR_s}{R_P}\right\} \tag{2.2}$$

Where,

I_{O1} and I_{O2} are the reverse saturation currents of diode 1 and 2 respectively

α_1 and α_2 represents the diode ideal constant.

V_{T1} and V_{T2} are thermal voltages of their respective diodes.

J.A Gow et.al [6] developed a general model of solar PV array which can be implemented on various simulation platforms. Model is used to obtain P-V and I-V characteristics for the cell by taking temperature and irradiance as input parameter. The developed model is suitable for the use with power electronics interface.

2.4 POWER ELECTRONICS INTERFACE

Power electronic converter is used to interface the PV array to dc bus to perform three major functions including step up/step down the PV voltage, regulate the varying dc output voltage of PV array and implement the MPPT of solar array to ensure operation at maximum efficiency. However, there are various topologies of DC-DC converter including buck, boost, push pull, half bridge, full bridge, fly-back, buck-boost etc. The choice of topology depends on system requirements and its applications.

Yungtaek Jang et.al [7] developed a new two inductor, two switch boost converter topology. Proposed converter gives a wide range of output voltage regulation with a variable load and input voltage. An auxiliary transformer is also incorporated with this converter to couple the current paths of the two boost inductors. Authors verified the performance of proposed two inductor boost converter with a 1KW prototype circuit designed for 40-70V battery voltage input and deliver upto 2.9 A at 380V output.

Ahmed H. El Khateb et.al [8] presented a combination of cuk and buck DC-DC converter for a standalone PV system. A MPPT control technique is implemented with the converter to provide a constant voltage/current to battery even under the changing atmospheric conditions. The proposed system has been tested under different operating conditions.

Hyuntae Choi et.al proposed a solution to reduce the transformation stages without changing the standard architecture of the system. A high gain DC-DC converter has been proposed in this paper for multi string PV system architecture. Authors simulate a 1MW PV system by using MATLAB/Simulink and PLECS block set.

Performance of the system has been analysed for three different cases.

1. Constant solar irradiance.
2. Fast changing irradiance.
3. Grid voltage sag.

T.Shanti et.al [9] proposed a boost converter and line commuted inverter with maximum power point tracking control for solar photovoltaic power generation systems. The proposed controller delivers the maximum power to the utility grid. Author developed a laboratory purpose prototype for the proposed system and verified the results.

Amudhavalli D. et.al [10] proposed a new topology of DC-DC boost converter for solar photovoltaic power generation system. This topology comprises a interleaved soft switching boost converter (ISSBC) with maximum power point tracking control. Proposed converter minimizes the switching losses by adopting a resonant soft switching method. Advanced P&O MPPT technique has been used in this work to increase the efficiency of the system. The model has been simulated on MATLAB/Simulink platform as well as hardware implementation also done by using this boost converter topology authors are able to reduce input current ripple and output voltage ripple.

2.5 MAXIMUM POWER POINT TRACKING ALGORITHMS

MPPT control is necessary in order to track the maximum power point of the PV array. These MPPT techniques are based on the reference voltage or reference current signal of the PV system which is adjusted in order to achieve maximum power point. These techniques includes perturb and observe, incremental conductance, constant voltage, open circuit voltage, short circuit current, extreme seeking control and hybrid etc.

F. Z. Hamidon et.al [11] presented a model of PV array with most widely used P & O maximum power point tracking algorithms. This model has been used to obtain PV array characteristics T different irradiance and temperature values. Further the authors analysed the characteristics of the model on the basis of other parameters also like series resistance, shunt resistance and series parallel combination of PV modules.

Ali Reza Reisi et.al [12] proposed and implemented variety of maximum power point tracking algorithms. Basically review paper and reclassified MPPT techniques under three major families i.e. offline, online and hybrid methods. This classification forms a platform for future research works. Authors categorized MPPT methods according to the control signal generation and behavior of photovoltaic system when it is leading towards steady state.

M. Abdulkadir et.al [13] designed and simulate a system incorporated with maximum power point tracking algorithm with a high frequency boost converter. Designed controller is able to track the MPP of PV panel by the adjustment of the duty cycle of the switch used in the boost converter. MATLAB/Simulink software is used to develop the designed model.

Developed model tested under the practical environmental conditions for different loading levels. Authors also modified the original incremental conductance algorithm and found new incremental conductance MPPT algorithm more efficient.

Hairul Nissah Zainudin et.al [14] compared two MPPT techniques namely incremental conductance and P & O on the basis of simplicity, digital or analogical implementation, speed of convergence, hardware required for implementation, cost etc. Comparative analysis is carried out by keeping current and voltage as sensing element and by varying solar irradiance and temperature. MATLAB/Simulink platform have been used to carried out the results in terms of efficiency, energy yield etc.

Mostafa Mosa et.al [15] proposed a modified MPPT controller using a model predictive control. Developed controller has been implemented using DC-DC multilevel converter which is used to step up the small dc voltage. Performance of designed system has been analyzed under different solar irradiance and temperature conditions on a MATLAB/Simulink platform.

2.6 INVERTER TOPOLOGIES FOR GRID CONNECTED PV SYSTEMS

Luigi G. Junior et.al [16] presented the evaluation of different converters for solar photovoltaic applications. According to the authors the most suitable topology uses a boost stage and one inverter stage cascaded. Transformer integrated topologies have low efficiency and high frequency transformer. This paper presented the comparative simulated result for various topologies.

Soeren Baekhoej Kjaer et.al [17] reviewed the inverter topologies available for single phase grid connection. Authors classified the inverter under four categories:

1. The number of power processing stages in cascade.
2. The type of power decoupling between the PV modules and single phase grid.
3. Whether utilizes a transformer (line or high frequency) or not.
4. The type of grid connected power stage.

Quan Li et.al [18] presented a study on topologies available for the PV module integrated converters below 500 W range. Authors classified the topologies in three major categories based on dc link configuration. The paper provides a useful framework for future research purpose as the authors also discussed advantages and disadvantages of each module integrated converter topology. Three topology of MIC are;

1. MIC with a DC link: - In this topology the power conversion process can be divided into two different stages i.e DC-DC and DC-AC conversions.

2. MIC with a Pseudo DC link: - IN this MIC topology DC-AC conversion stage operates at power frequency and achieved greatest interest of researches and advantageous over the two topologies.

3. MIC without DC link: - This topology reduces the need of dc link in power conversion process. This topology may lead the future generation module integrated converter for solar photovoltaic PV system.

Frptz Schimpf et.al [19] presented a review for low and medium level grid connected solar photovoltaic inverters, especially for rooftop applications. Again the authors classified the inverters according to the configuration of power stages, use of transformer and type of PV system. According to this review transformer less topologies are advantageous over the other topologies in terms of cost, weight etc.

2.7 CONTROL STRATAGIES FOR GRID CONNECTED SOLAR PV SYSTEMS

DC-AC converter stage should inject sinusoidal current in the grid i.e. current in phase with the grid voltage. Number of control techniques have been reported in literature for grid connected solar photovoltaic systems.

Sachin Jain et.al [20] proposed a highly efficient single stage inverter topology for grid integration of solar photovoltaic system. Developed topology provides better utilization of PV array as well as low cost and compact size. Authors have done complete steady state analysis of proposed topology. In this topology PV array behaves as a floating source for grid and hence increased the safety of the complete system. THD of current is restricted as per grid standards.

Linda Hassaine et.al [21] proposed , simulated and validate a digital control scheme based on the phase shifting of inverter voltage with respect to the grid voltage for grid connected photovoltaic system. Proposed scheme provide power factor control with less number of SPWM patterns for large range of output current.Output current of inverter is the function of angle between output voltage of inverter and the grid voltage. So by modifying this angle we can control the inverter output current. Developed controller does not require a complicated hardware and provides a smart approach for active and reactive power control.

Shuai Jiang et.al [22] proposed a control technique for single phase grid connected low power solar photovoltaic system. Given system contains a DC-DC boost half bridge converter which consist a high frequency plug-in repetitive current controller is proposed for the control of PV inverter. Proposed system guaranteed low THD under heavy and low load conditions.

A variable step MPPT algorithm has been implemented in DC-DC boost converter for fast tracking of MPP of PV system. This paper provides validated simulation and hardware results.

H.Toodeji et.al [23] proposed a STATCOM integrated solar photovoltaic system for grid connection. In proposed control technique STATCOM accomplish the compensating tasks(reactive power compensation, voltage fixing etc.). Authors also concluded that with integration of STATCOM solar PV system does not require a DC/DC conversion stage and MPPT control because STATCOM regulates DC voltage at optimal value. Paper presents a simulated system in MATLAB environments with verified results.

Yu-Kang Lo et.al [24] presented a new combined grid connection and power factor correction technique for single phase grid PV system. Proposed system also contains charge storage functionality. Proposed control technique simplified the hardware structure and provides many functions even at low cost. Authors also implemented a power management algorithm in order to maintain the correct power relation in between PV system, battery bank and the grid. Satisfactory experimental results are provided by the developed system for 1KW PV system with nearly unity power factor at grid side.

2.8 POWER QUALITY ISSUES IN GRID CONNECTED PV SYSTEMS

Grid connected solar photovoltaic systems consists at power electronics converters in order to convert DC to AC, these converter inject harmonics into grid. PV system suffers from the output voltage fluctuations due to non-uniform irradiance conditions. These all things make PV system unstable in terms of grid connection.

S.K Khardem et.al [25] presented a technical review of power quality problems associated with the renewable energy based distributed generation system. This review paper also described the role of custom power devices like STATCOM, DVR and UPQC in power quality improvement. Authors explained that output of PV panel depends on the solar intensity and atmospheric conditions and power quality issues are not only because of solar irradiance but also depend upon the inverters, filters, controlling mechanism etc. According to the authors a special attention is required to maintain the voltage profile and power flow. Custom power devices are found to be very capable for integration of renewable energy based generating plants into the grid.

Masoud Farhoodnea et.al [26] presented a dynamic PQ analysis of highly penetrated grid connected photovoltaic systems in distribution network system under varying atmospheric conditions. From the results and discussions it can be observed that the high penetrated grid connected PV systems may become a cause of power quality problems such as voltage flicker, power factor reduction and harmonics etc.

2.9 EFFECT OF PV PENETRATION ON LOW VOLTAGE GRID

Shivananda Pukhrem et.al [27] presented a review understanding the challenges faced while integrating large PV plants into the grid and resolve them in order to maintain secure, reliable and robust electrical power system network without any grid reinforcement.

Jeremy D. Watson et.al presents a case study of simulating the entire LV network from a single utility, comprising transformers and their associated distribution feeders. Various solar PV penetration levels are added to the model and the power flow results are presented. From these results, possible maximum limits of solar PV penetration are investigated and measures to alleviate overvoltage problems are simulated.

Guangya Yang et.al [28] presented a paper that discusses the modeling requirements for PV system integration studies, as well as the possible techniques for voltage rise mitigation at low voltage (LV) grids for increasing PV penetration potential solutions are also mentioned.

Farhad Shahnia et.al [29] presented a comprehensive voltage imbalance sensitivity analysis and stochastic evaluation based on the rating and location of single-phase grid-connected rooftop photovoltaic cells (PVs) in a residential low voltage distribution network. The voltage imbalance at different locations along a feeder is investigated. In addition, the sensitivity analysis is performed for voltage imbalance in one feeder when PVs are installed in other feeders of the network.

2.10 CONCLUSION

This chapter has given a brief outline of the literature survey carried out during the course of this dissertation.

CHAPTER 3

SOLAR PV TECHNOLOGY

3.1 INTRODUCTION

This chapter presents a brief overview of solar PV technology. A detailed information regarding the solar photovoltaic system design is also provided by this text.

3.2 SOLAR PV TECHNOLOGY

Solar energy can be utilized with the help of two technologies i.e. solar thermal technology and solar photovoltaic technology. In India, solar thermal technology for power generation is limited. However there is a drastic advancement in photovoltaic technology. The power generated from PV system can be expressed using the following equation:

$$P = Ax^2 + Bx + C \text{ (Watts)} \quad (3.1)$$

Where, P = power generation (watts)

x = solar radiation and

A, B, C are the constants, which may be derived from the measured data.

The photovoltaic (PV) cell is the smallest constituent in a PV system, Photovoltaic Cells are basically made up of a PN junction. When solar irradiance strikes at the cell surface, the photons are absorbed by the atoms of semiconductor and electrons get free from the negative layer. These free electrons find their way through an external circuit toward the positive layer making flow of electric current from the positive to the negative layer.

In 1839, Edmond Becquerel observed photovoltaic effect while working on solid-state physics. In 1878, Adam & Day published a paper on this effect. The first thin film solar cell was fabricated in 1883 by Fxitz. Due to major research in various coming years along the line finally in 1954 scientist from Bell labs fabricated a PV cell with an efficiency of 6%.

The basic structure of a PV panel is Photovoltaic cells, which work on the principle of photovoltaic effect. These PV cells have to be configured in series and parallel as the potential induced by a single pv cell is very less nearly 50mV. The relationship among the voltage and current of the PV cell is non-linear in shape.

Solar cells are just like batteries, when connected in series current remains the same, but voltage increases and when they connected in parallel voltage remains same while current increases. A PV cell mainly made-up of silicon and rest constitutes various other semiconductor material which are used in LSIs & other electronic equipment's. A cross-sectional view of Solar cell is shown in Figure 3.1

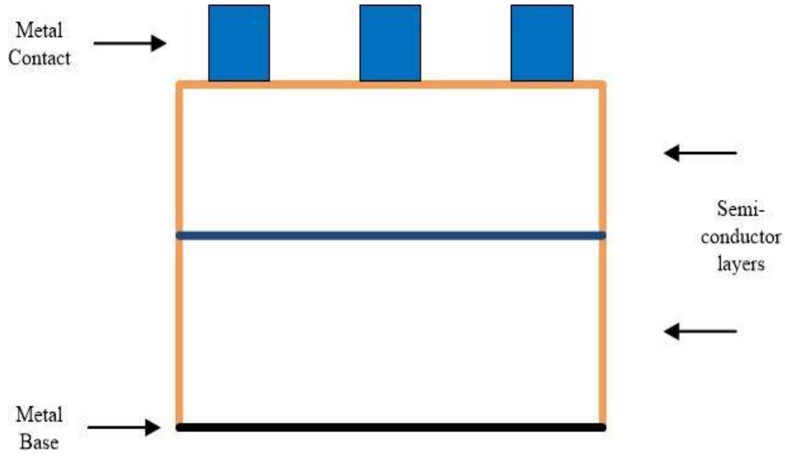


Figure 3.1 Cross Sectional View of Solar Cell

These PV cells when connected in a specified configuration to produce the desired voltage and current, the structure is called a photovoltaic module. The interconnected cells have their connections made from the top and bottom layer which is made up of plastic and metal respectively. To increase the strength of structure an outer frame is attached so that it can easily be mounted this complete package is called a module or panel, a PV system is made-up of these module.

With the growing demand of solar power new technologies are being introduced and existing technologies are developing. There are four types of solar PV cells:

- ❖ Single crystalline or mono crystalline
- ❖ Multi- or poly-crystalline
- ❖ Thin film
- ❖ Amorphous silicon

Single Crystalline or Mono Crystalline

These are widely available and the most efficient cell materials. They produce the most power per square foot of module. Each cell is made up from a single crystal. To maximize the cell counts in module, the crystals are further divided into rectangular parts.

Polycrystalline Cells

It is made from similar silicon material except that instead of being grown into a single crystal, they are melted and poured into a mold. This mold makes a square block which can be divided into square wafers resulting in less waste of space and material than round single-crystal wafers.

Thin Film Panels

Thin film panels are the newest technology in the field of solar cell technology. Thin film materials are Copper indium dieseline, cadmium telluride, and gallium arsenide. They are directly deposited on glass, stainless steel, or other compatible substrate materials. Most of the thin film materials perform slightly better than crystalline modules under low sun light conditions. Thickness of thin film is few micro meters or less.

Amorphous Silicon

This technology is newest in the area of thin film technology. In this technology amorphous silicon vapour is deposited on a couple of micro meter thick amorphous films on stainless steel rolls. This technology utilizes only 1% of the material in comparison with crystalline silicon.

Table 3.1 Efficiency of Different Type of Solar Cells

S.No.	**Cell**	**Efficiency (%)**
1	Monocrystalline	12 – 18
2	Polycrystalline	12 – 18
3	Thin film	8 – 10
4	Amorphous Silicon	6 – 8

3.3 EQUIVALENT CIRCUIT OF SOLAR CELL

The solar cell can be represented by the electrical model shown in Figure 3.1. Its current-voltage characteristic is expressed by the following equation (3.2):

$$I = I_l - I_o\left(e^{\frac{q(V-IR_S)}{AkT}} - 1\right) - \frac{V - IR_s}{R_{sh}} \tag{3.2}$$

where *I* and *V* are the solar cell output current and voltage respectively, I_0 is the dark saturation current, *q* is the charge of an electron, *A* is the diode quality factor, *k* is the Boltzmann constant, *T* is the absolute temperature and R_S and R_{SH} are the series and shunt resistances of the solar cell. R_S is the resistance offered by the contacts and the bulk semiconductor material of the solar cell. The origin of the shunt resistance R_{SH} is more difficult to explain. It is related to the non-ideal nature of the p–n junction and the presence of impurities near the edges of the cell that provide a short-circuit path around the junction. In an ideal case R_S would be zero and R_{SH} infinite. However, this ideal scenario is not possible and manufacturers try to minimize the effect of both resistances to improve their products.

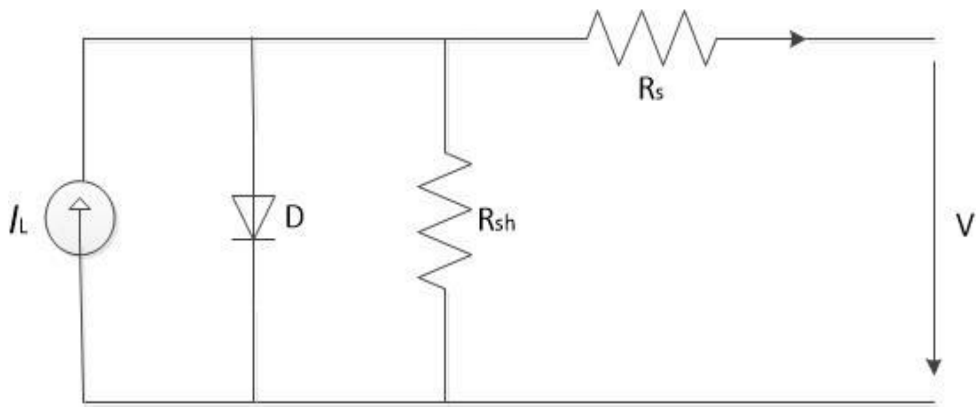


Figure 3.2 Equivalent Circuit of Solar cell

A PV panel is composed of many solar cells, which are connected in series and parallel so the output current and voltage of the PV panel are high enough to the requirements of the grid or equipment. Taking into account the simplification mentioned above, the output current-voltage characteristic of a PV panel is expressed by equation (3.3), where n_p and n_s are the number of solar cells in parallel and series respectively.

$$I \approx n_p I_l - n_p I_o\left(e^{\frac{q(V-IR_S)}{AkTn_S}} - 1\right) \tag{3.3}$$

Open Circuit Voltage, Short Circuit Current and Maximum Power Point

Two important points of the current-voltage characteristic must be pointed out: the open circuit voltage *VOC* and the short circuit current *ISC*. At both points the power generated is zero. *VOC* can be approximated from (1) when the output current of the cell is zero, i.e. I=0 and the shunt resistance *RSH* is neglected. It is represented by equation (3.4). The short circuit current *ISC* is the current at V = 0 and is approximately equal to the light generated current *IL* as shown in equation (3.5).

$$V_{oc} \approx \frac{AkT}{q} \ln\left(\frac{I_L}{I_o} + 1\right) \tag{3.4}$$

$$\mathrm{I_{sc}} \approx \mathrm{I_L} \tag{3.5}$$

The maximum power is generated by the solar cell at a point of the current-voltage characteristic where the product *VI* is maximum. This point is known as the MPP and is unique, as can be seen in Figure 3.2, where the MPP are represented.

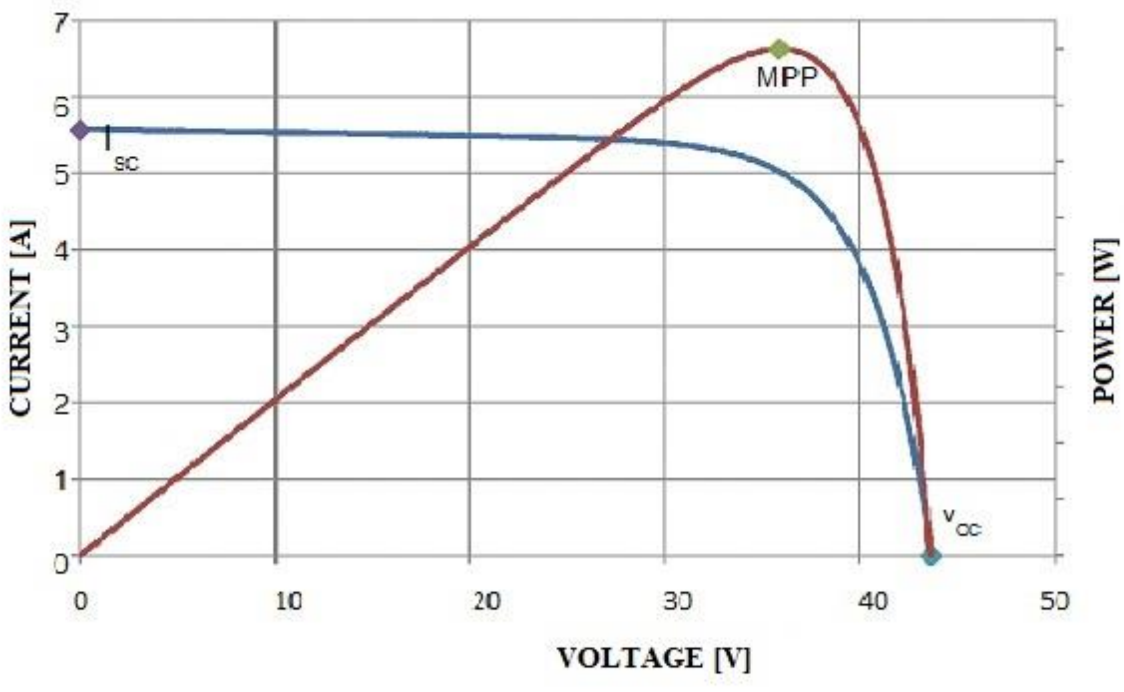


Figure 3.3 Important Points in the Characteristic Curve of Solar PV

3.4 PERFORMANCE OF SOLAR PV AT VARYING METEOROLOGICAL CONDITIONS

PV modules are characterized at STC but meteorological parameters like solar irradiance and temperature are not constant under practical conditions. Amount of solar irradiance reaching at earth surface varies greatly because of various meterological and atmoshpheric parameters like water vapour molecules, number of gaseous molecules, aerosoles, cloud, change in position of sun etc. Under such practical conditions, the impact of these parameters is utmost important on PV power output.

3.4.1 Performance of Solar PV at Varying Solar Irradiance

With the increasing solar irradiance both the open circuit voltage and the short circuit current increases and hence the maximum power point varies. The solar irradiance or insolation is varying continuously, so the characteristics changes continuously. At different locations this data also changes with time. As irradiance increases, the current increases greatly while little effect on the voltage, hence the power increases with increased irradiance. This can be shown by the Figure 3.4

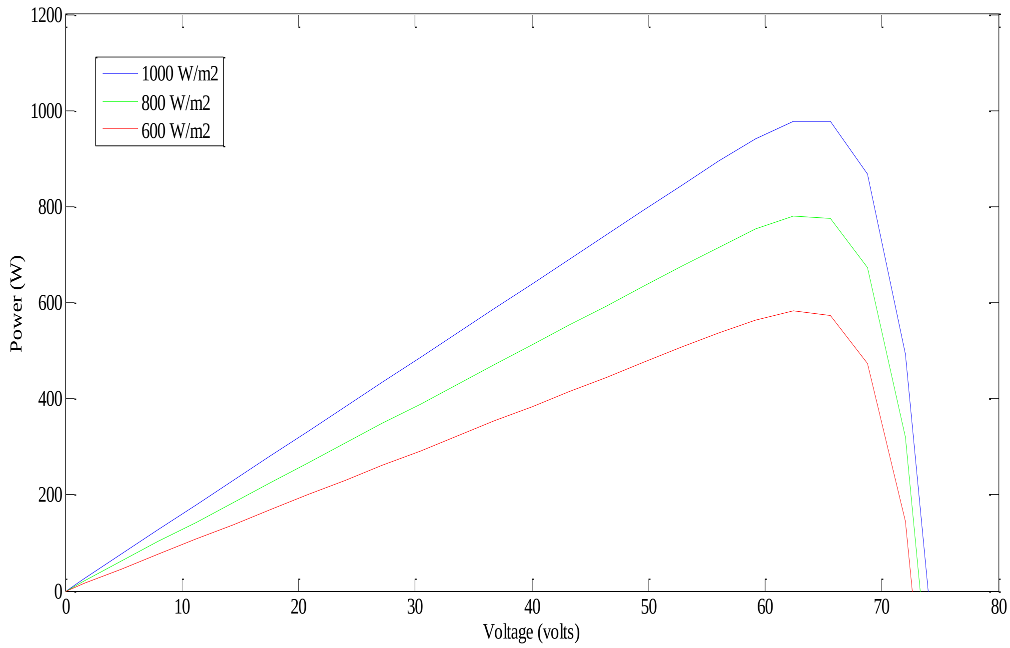


Figure 3.4 Power- Voltage Curve of Solar PV at Varying Irradiance

3.4.2 Performance of Solar PV at Varying Temperature

As the temperature increases the rate of photon generation increases thus reverse saturation current increases rapidly and this reduces the band gap. Hence this leads to marginal changes in current but major changes in voltage. The cell voltage reduces by 2.2mV per degree rise of temperature. Temperature acts like a negative factor affecting solar cell performance. Therefore solar cells give their full performance on cold and sunny days rather on hot and sunny weather. The effect of varying temperature can be shown in Figure 3.5. As temperature increases, the voltage decreases substantially while the current undergoes insignificant increase. As a result, the power decreases with increasing temperature.

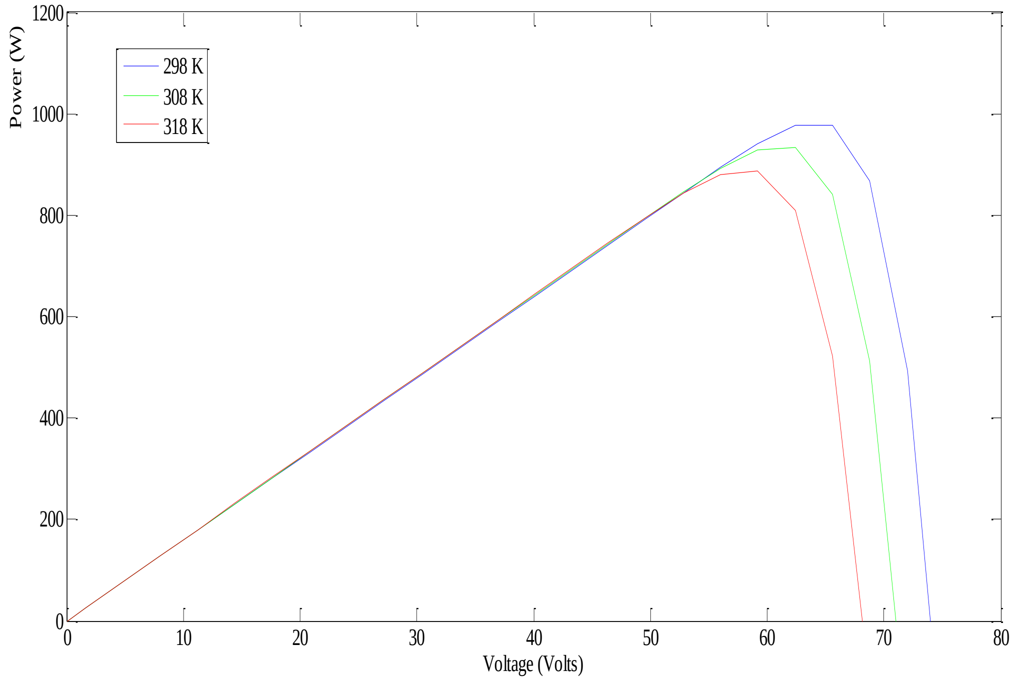


Figure 3.5 Power- Voltage Curve of Solar PV at Varying Temperature

3.5 TYPES OF SPV SYSTEM DESIGN

Solar system design can be design in different manners. But there are two basic design considerations, they are-

1. Stand alone
2. Grid connected

Standalone Systems

These systems can be utilized to feed power to small loads, like water pumps and street lights and to the huge loads of a house. The main components of a stand-alone system include solar panels, a charge controller and batteries. An inverter can be added to the design for loads that demands AC power. Output voltage of a panel can be control by an MPPT controller in order to increase the efficiency of the power deliver batteries and load. The components of system vary according to the load requirements and the number of hours for operation during the night. Depending on the load operating during the day the battery may only need to last minutes to hours. For the systems that have loads operating during night, batteries are selected according to the number of hours of operation. Continuous operation of system requires the knowledge of dependability of the load to calculate the amount of reserve energy the system must have to provide. The stand-alone system has number of advantages like independency from the utility grid, replacement of petroleum-fuelled generators and provides cost effective solution to remote areas. The main disadvantages are the cost and replacement of equipment and the loss of power during periods of poor solar irradiance.

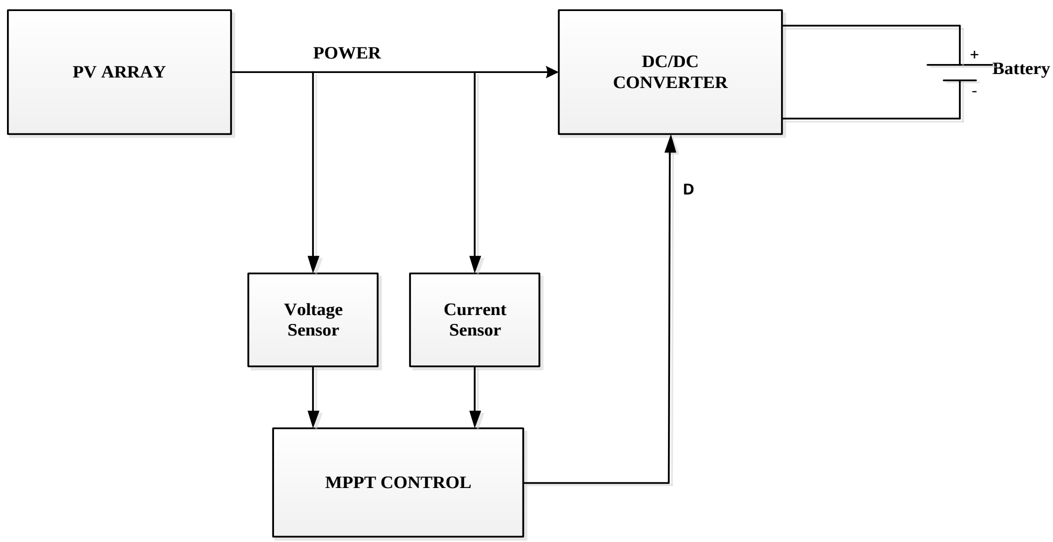


Figure 3.6 Standalone Solar PV System

Grid Connected Systems

Grid connected systems are mainly composed of a number of PV arrays, which convert the sunlight to DC power and a power electronics unit that changes the DC power to AC power. The produced AC power is fed to the grid and utilized by the local loads. Storage devices can be used to improve the availability of the power generated by the SPV systems. Grid integrated systems have the provisions for the customer to sell back the produced power at cost to the utility grid.

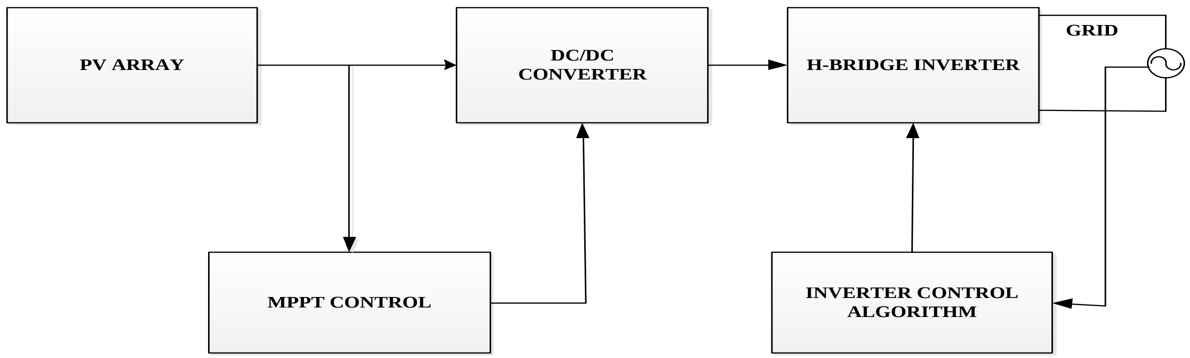


Figure 3.7 Single Phase Grid Connected Solar PV System

3.6 CONCLUSION

Various types of design harnessing solar energy with the help of solar PV systems has been explained in this chapter along with the important points in the power-voltage and current-voltage curves of PV system. Also, the performance of Solar PV at varying meteorological parameters is discussed.

CHAPTER 4

CONTROL STRATERGIES FOR SOLAR PV SYSTEM

4.1 INTRODUCTION

This chapter presents a brief overview of different control strategies for grid connected solar PV systems such as MPPT, inverter control and battery charging and discharging.

4.2 MAXIMUM POWER POINT TRACKING ALGORITHMS

As was previously explained, MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array. As shown by the Figure 4.1 and Figure 4.2

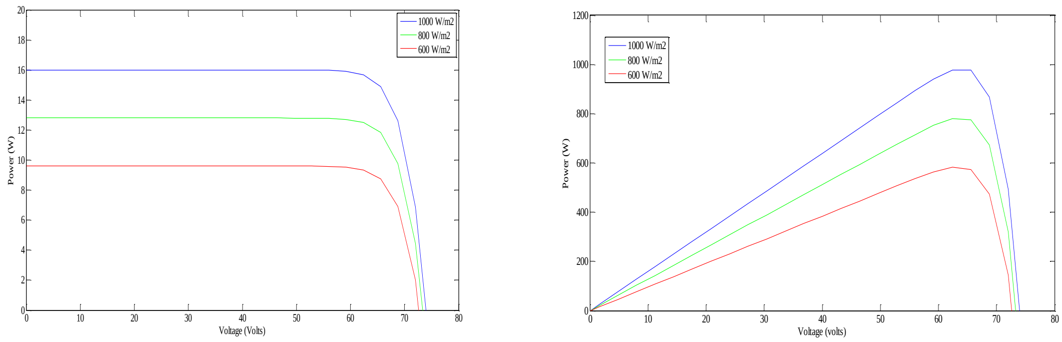


Figure 4.1 Variation of Voltage and Power due to Varying Irradiation

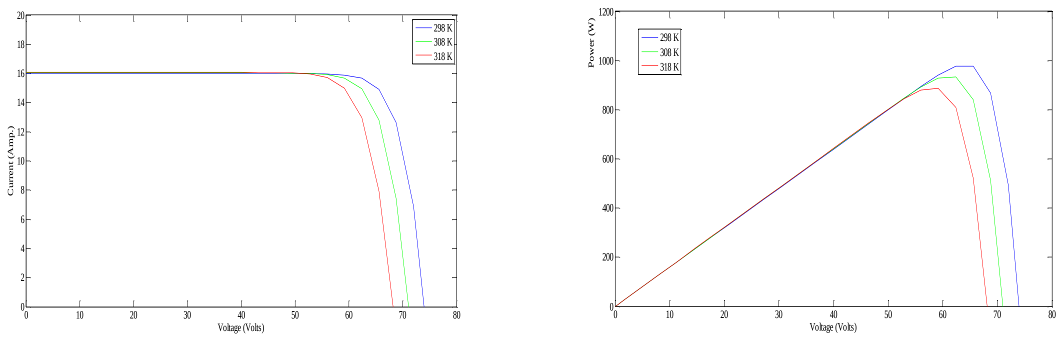


Figure 4.2 Variation of Voltage and Power due to Varying Temperature

Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity etc.

Among these techniques, the P&O and the Incremental Conductance algorithms are the most common. These techniques have the advantage of an easy implementation but they also have drawbacks. Other techniques based on different principles are fuzzy logic control, neural network, fractional open circuit voltage or short circuit current, current sweep, etc. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the P-V curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented. In the next section the most popular MPPT techniques are discussed.

Both P&O and Incremental Conductance algorithms are based on the "hill-climbing" principle, which consists of moving the operation point of the PV array in the direction in which power increases. Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant. The advantages of both methods are the simplicity and low computational power they need. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions.

4.2.1 Perturb and Observe (P&O)

The P&O algorithm is also called "hill-climbing", but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. On the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power. A flowchart illustrating this method is shown in Figure 4.3

If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented. The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP.

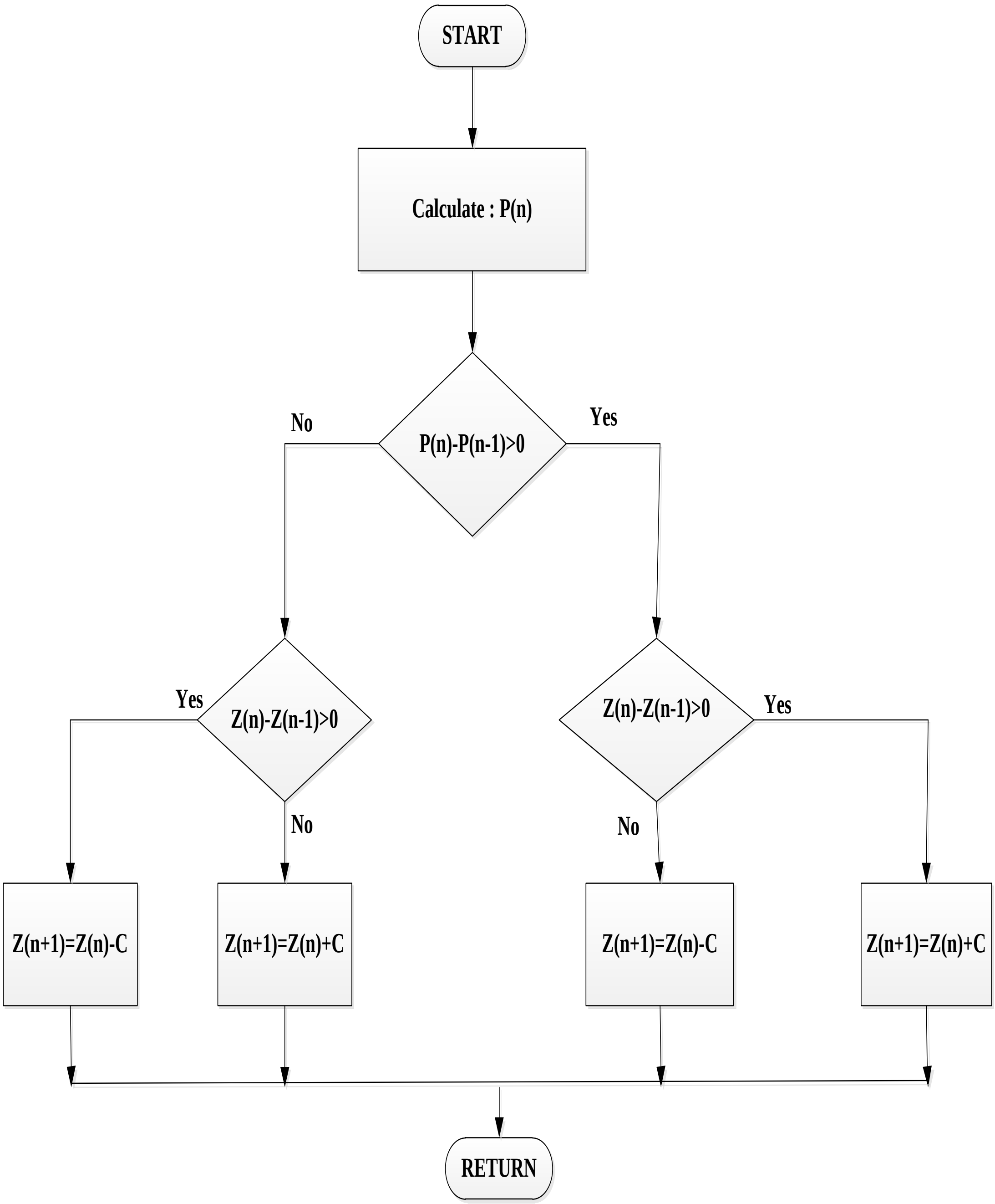


Figure 4.3 Flowchart for Perturb & Observe MPPT Technique

4.2.2 Incremental Conductance

Incremental conductance method is based on the fact that the slope of the PV module curve is zero at maximum power point. This slope will be positive for values of output power smaller then MPP and negative for output power greater then maximum power point.

Maximum output power can be obtained by using the derivative of PV output power with respect to voltage and equating this to zero.

$$\frac{dP}{dV} = I + v\frac{dI}{dV} = 0 \tag{4.1}$$

By using equation (4.6) the following equation can be obtained

$$\frac{dI}{dV} \cong \frac{\Delta I}{\Delta V} = -\frac{I_{MPP}}{V_{MPP}} \tag{4.2}$$

$$\frac{dP}{dV} = 0 \qquad \frac{\Delta I}{\Delta V} = -\frac{I}{V} \qquad \text{at MPP} \tag{4.3}$$

$$\frac{dP}{dV} > 0 \qquad \frac{\Delta I}{\Delta V} > -\frac{I}{V} \qquad \text{left side of MPP} \tag{4.4}$$

$$\frac{dP}{dV} < 0 \qquad \frac{\Delta I}{\Delta V} < -\frac{I}{V} \qquad \text{right side of MPP} \tag{4.5}$$

Instantaneous conductance is compared with the incremental conductance in order to track the maximum power point. After achieving the MPP, the operation of PV module is forced to remain at this point unless a change in current occurs as a result of varying meteorological parameters which leads variation in MPP. The flowchart for incremental conductance technique is presented in Figure 4.4.

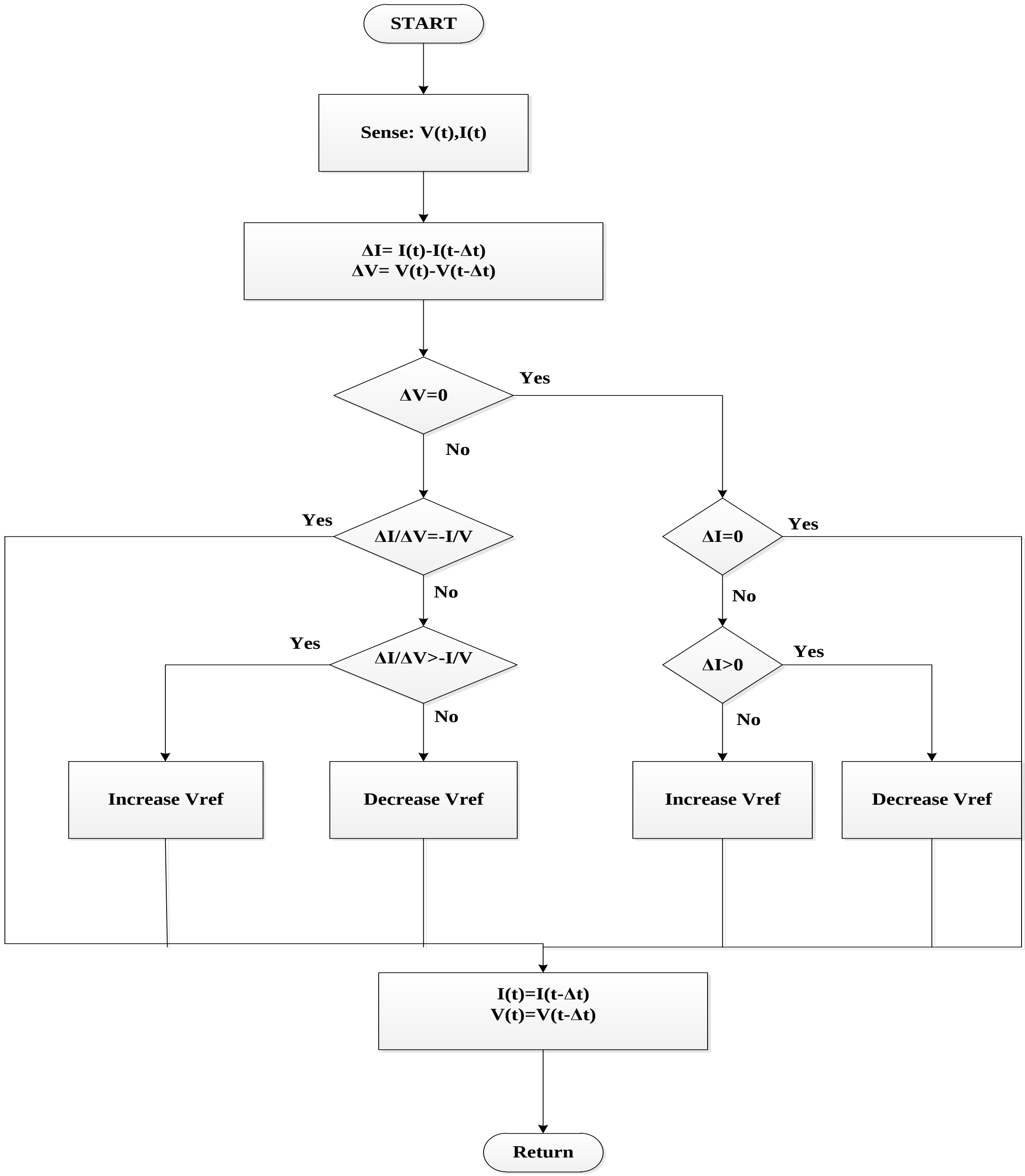


Figure 4.4 Flowchart for Incremental Conductance MPPT technique

4.2.3 Fuzzy Logic Control

The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. Microcontrollers have also helped in the popularization of fuzzy logic control.

The fuzzy logic consists of three stages

- Fuzzification
- Inference system and
- Defuzzification.

Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions, like the ones in Figure 4.5, are used to associate a grade to each linguistic term. The number of membership functions used depends on the accuracy of the controller, but it usually varies between 5 and 7. In Figure 4.7 seven fuzzy levels are used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big).

The values *a*, *b* and *c* are based on the range values of the numerical variable. In some cases the membership functions are chosen less symmetric or even optimized for the application for better accuracy.

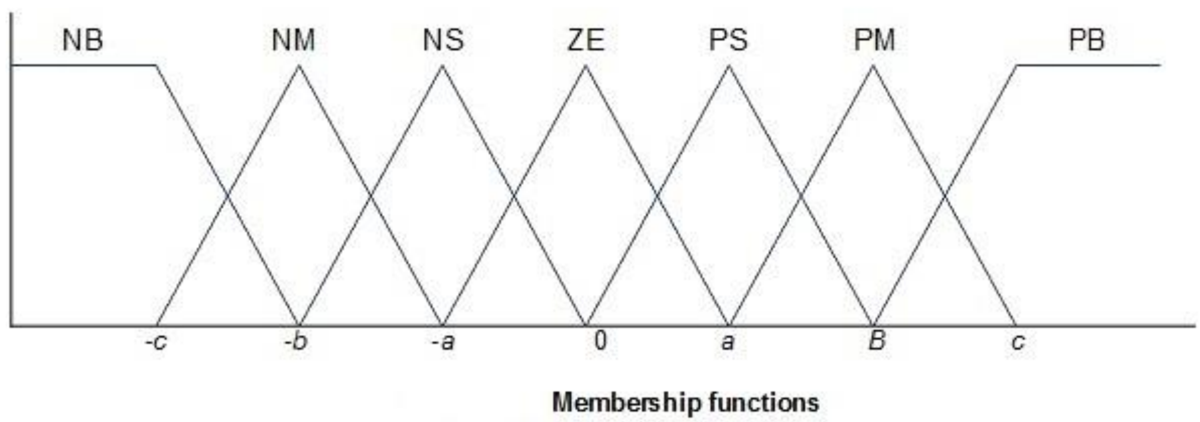


Figure 4.5 Membership Functions of Fuzzy Logic

The inputs of the fuzzy controller are usually an error, E, and the change in the error, ΔE. The error can be chosen by the designer, but usually it is chosen as ΔP/ΔV because it is zero at the MPP. Then E and ΔE are defined as follows:

$$E = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{4.6}$$

$$\Delta E = E(k) - E(k-1) \tag{4.7}$$

The output of the fuzzy logic converter is usually a change in the duty ratio of the power converter, ΔD, or a change in the reference voltage of the DC-link, ΔV. The rule base, also known as rule base lookup table or fuzzy rule algorithm, associates the fuzzy output to the fuzzy inputs based on the power converter used and on the knowledge of the user. Table I shows the rules for a three phase inverter, where the inputs are E and ΔE, as defined in (4.11) and (4.12), and the output is a change in the DC-link voltage, ΔV. For example, if the operating point is far to the right of the MPP, E is NB, and ΔE is zero, then to reach the MPP the reference voltage should decrease, so ΔV should be NB (Negative) to move the operating point towards the MPP.

The last stage of the fuzzy logic control is the defuzzification. In this stage the output is converted from a linguistic variable to a numerical crisp one again using membership functions as those in Figure 15. There are different methods to transform the linguistic variables into crisp values. It can be said that the most popular is the centre of gravity method. However the analysis of these methods is beyond the scope of this thesis.

The advantages of these controllers, besides dealing with imprecise inputs, not needing an accurate mathematical model and handling nonlinearity, are fast convergence and minimal oscillations around the MPP. Furthermore, they have been shown to perform well under step changes in the irradiation. However, no evidence was found that they perform well under irradiation ramps. Therefore, their performance under the conditions specified for testing the dynamic MPPT efficiency is unknown. Another disadvantage is that their effectiveness depends a lot on the skills of the designer.

4.2.4 Neural Networks

Another MPPT method well adapted to microcontrollers is Neural Networks. They came along with Fuzzy Logic and both are part of the so called “Soft Computing”.

The simplest example of a Neural Network (NN) has three layers called the input layer, hidden layer and output layer, as shown in Figure 4.7. More complicated NN’s are built adding more hidden layers. The number of layers and the number of nodes in each layer as well as the function used in each layer vary and depend on the user knowledge. The input variables can be parameters of the PV array such as VOC and ISC, atmospheric data as irradiation and temperature or a combination of these. The output is usually one or more reference signals like the duty cycle or the DC-link reference voltage.

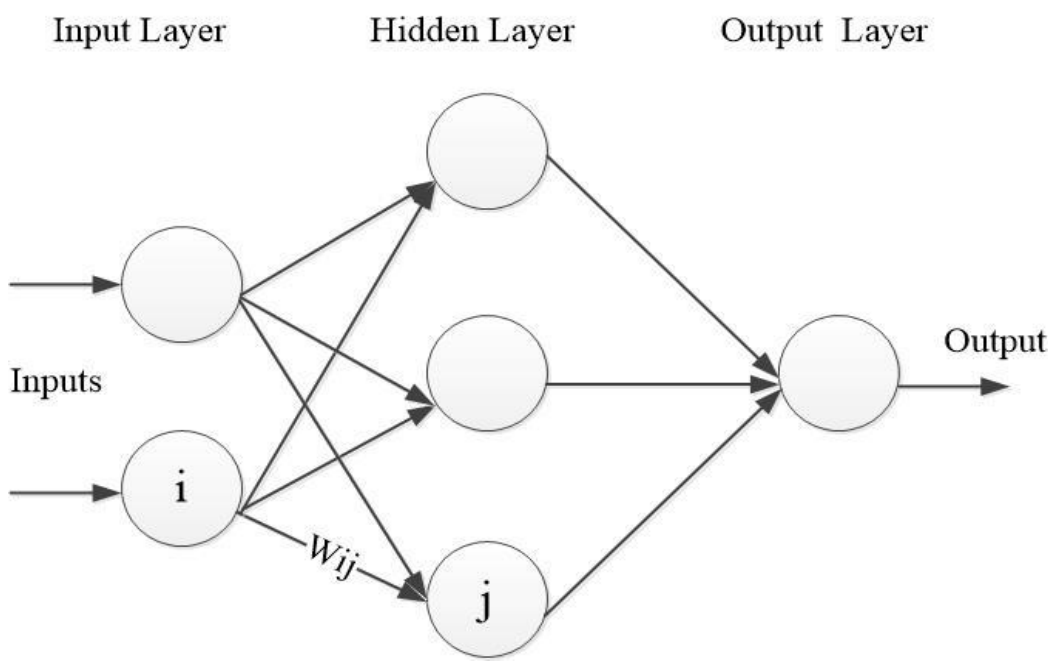


Figure 4.6 General Architecture of Neural Network

The performance of the NN depends on the functions used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted. In Figure 16 the weight between the nodes *i* and *j* is labelled as w_{ij}. The weights are adjusted in the training process. To execute this training process, data of the patterns between inputs and outputs of the neural network are recorded over a lengthy period of time, so that the MPP can be tracked accurately.

The main disadvantage of this MPPT technique is the fact that the data needed for the training process has to be specifically acquired for every PV array and location, as the characteristics of the PV array vary depending on the model and the atmospheric conditions depend on the location. These characteristics also change with time, so the neural network has to be periodically trained.

Most of the MPPT algorithms developed over the past years have been reviewed in the previous sections. Some of them are very similar and use the same principle but expressed in different ways. The most popular MPPT algorithms are P&O, InCond and Fuzzy Logic. It makes sense because they are the simplest algorithms capable of finding the real MPP. However, they have some disadvantages, as discussed earlier. They were selected because of their simplicity and popularity.

4.3 INVERTER CONTROL ALGORITHMS

The classic configuration of a grid connected Solar PV system consists basically of two parts. The first stage is the energy supply represented by a photovoltaic array. In the output stage, an inverter is used to convert and adapt the energy accumulated in an intermediate storage element (dc-link capacitor), to be consistent with the voltage and power quality requirements of the utility grid.

For low power photovoltaic systems, the classical two-level inverter is typically employed as the interface between dc-link and grid for high power medium voltage applications, Multilevel Converter is widely used.

Several control techniques have been proposed for grid connected applications in the last few decades. The controllers attempt to achieve stability, low harmonic content, fast dynamic response and simplicity. However, trade-offs are usually required. The classical hysteresis current controller, for example, has an inherent stability and fast and robust dynamic response, but is affected by variable switching frequency and interference between phases in isolated neutral three-phase systems. These weaknesses are overcome with the voltage-oriented control method, which achieves constant switching frequency and consequently a well-defined harmonic spectrum by controlling the load currents which are split into dq-components, according to the synchronous reference frame theory. On the other hand, its stability and dynamic performance are highly dependent on load parameters. The fast development of powerful microprocessors has been opening space for a new class of control techniques, due to advantages of flexibility and the ability to process complex on-line calculations. The predictive control technique makes use of these benefits to calculate the optimum control action among all the possibilities to fulfil certain predefined criteria. Nevertheless, the performance is susceptible to variations in load parameters. Another emerging control method, known as Direct Power Control, utilizes on-line estimations of control variables and a switching table to select the proper switching state. This technique has been shown to be very suitable for grid connected applications, since it regulates directly the instantaneous active and reactive powers.

4.3.1 Synchronous Reference Frame based Current Controller

DC-AC stage must only inject active component of grid current. So for this the steady state current error between the actual and desired grid current should remain zero at any grid frequency. Phase locked loop (PLL) tracks the phase of input voltage signal and generate unit voltage templates (sine and cosine components). The d-q components of currents passed by a filter which filter out high frequency harmonic components. Then again d-q frame is transformed back to 1-phase components. This current is then compared with source current and error between them is fed to Hysteresis-based PWM signal generator to produce final switching signals which are the pulses for inverter.

System terminal voltages are given as,

$$v_\alpha = V_m \cos(\omega t + \Phi) \tag{4.8}$$

And current are given as:

$$i_\alpha = I_m \cos(\omega t + \theta_n) \tag{4.9}$$

Following equation gives

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4.15}$$

i_d= In phase component of Grid current

i_q= Reactive component of Grid current

$$\begin{bmatrix} i_d = I\cos(\Phi - \theta_n) \\ i_q = -I\sin(\Phi - \theta_n) \end{bmatrix} \tag{4.16}$$

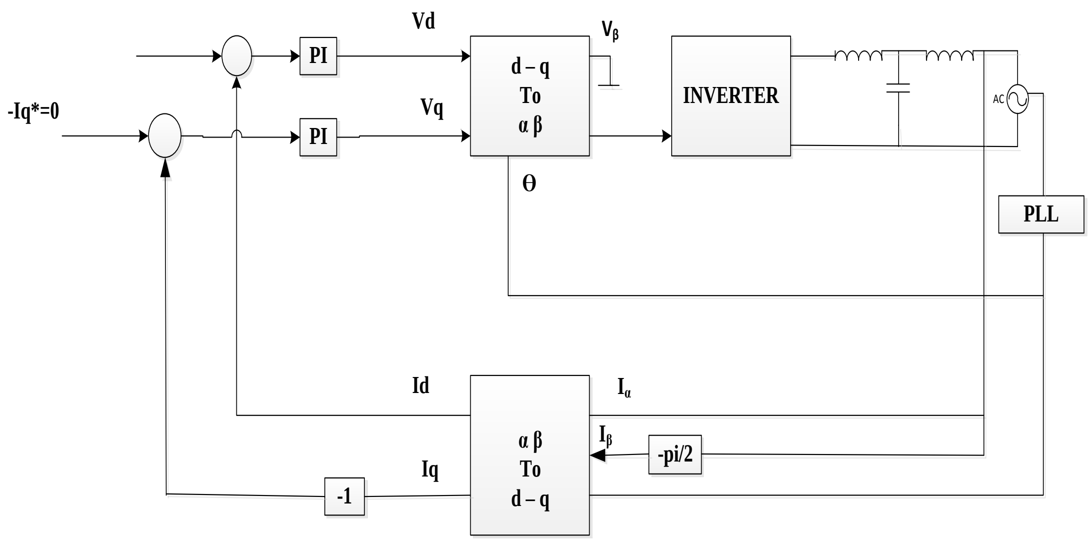


Figure 4.7 Reference Current Extraction using SRF Theory

These reference currents are compared with actual current and error between both will be the required amount of reactive current supplied by inverter. Error of current is used to generate pulses for inverter.

4.3.2 Digital PI based Current Controller

The PI control method can be used digitally to control the various parameters of inverters like current, voltage, etc. The digital PI control can be implemented to the system hardware by using microprocessors by programming the controlling algorithms.

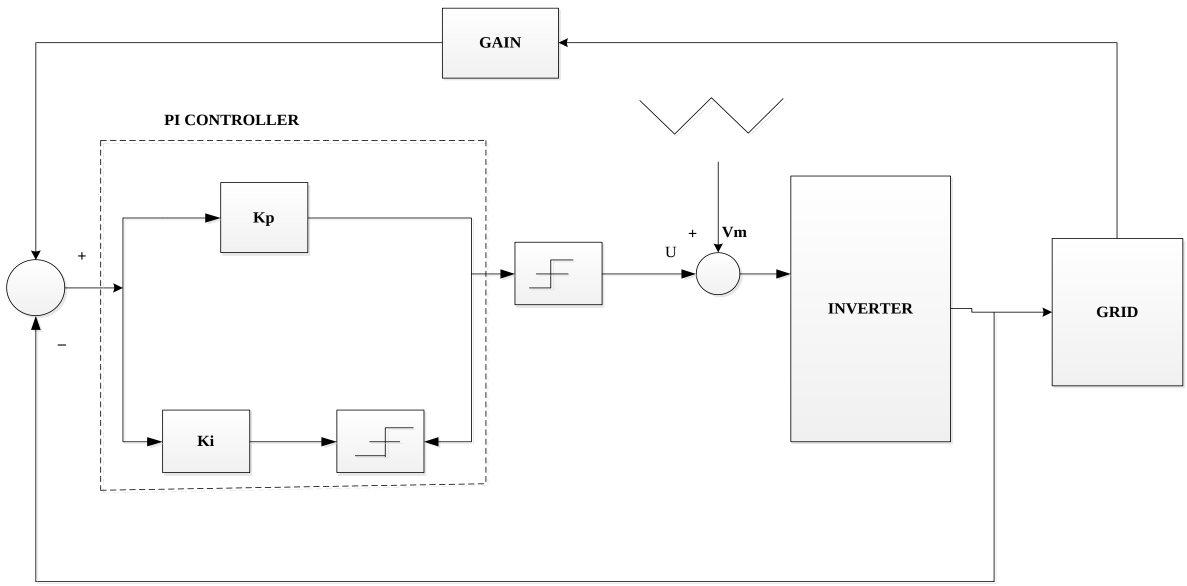


Figure 4.8 Inverter Control using PI Controller

PI algorithm is utilized by the controller to update the response or to minimize the error between reference current and inverter current. Reference current is the function of grid voltage and produced by sensing the grid voltage and convert it into current. This is done to maintain the invert output current at UPF and in phase with grid voltage. PI controller monitors the instantaneous error between the inverter output current and reference current. Finally this error signal is compared with a carrier signal to obtain the PWM signal of single phase inverter. The PI controller algorithm can be written as following equations

$$u(t) = Kpe(t) + Ki \int e(\tau)\, d\tau \tag{4.17}$$

Where,

$u(t)$ = control signal

$e(t)$ = error signal

Kp = proportional gain

Ki = integral gain

Discrete time domain equation for proportion gain can be directly applied directly as it was in the continuous form but integral gain requires approximations. Hence a method named as trapezoidal sum approximation can be utilized to obtain time domain form.

$$Kpe(t) = Kpe(k) \qquad (4.18)$$

$$Ki \int_{\tau=0}^{t} e\,(\tau)\,d\tau = Ki \sum_{i=0}^{k} \frac{h}{2} [e(i) + e(i-1)] \qquad (4.19)$$

$$t = k * h \qquad (4.20)$$

Where h denotes the sampling period and k is discrete time index, k=0, 1.....

$$u(k) = Kpe(k) + Ki \sum_{i=0}^{k} \frac{h}{2} [e(i) + e(i-1)] \qquad (4.21)$$

The heart of control lies in these two above mentioned equations. To ignore the need to calculate the full summation every time the summation is expressed as a running sum

$$sum\,(k) = sum\,(k-1) + [e(k) + e(k-1)] \qquad (4.22)$$

$$u(k) = Kp\,e(k) + Ki\,sum\,(k) \qquad (4.23)$$

4.3.3 Adaptive Notch Filter based Grid Synchronization Approach

Adaptive Notch filter based technique offers the compensation of harmonics current and reactive power with linear and nonlinear both type of loads. To maintain constant DC link voltage a PI controller is implemented.

Adaptive notch filter (ANF) approach is used to synchronize the interfaced PV system with grid to maintain the amplitude, phase and frequency parameters in power quality improvement. The signal is in the periodic form and is defined as

$$u(t) = \sum_{i=1}^{n} A_i \sin \varphi_i \quad where \;\; \varphi_i = \omega_i + \varphi_i \qquad (4.24)$$

Where A_i is anon zero amplitudes, ω_i is non-zero frequencies and phases $\varphi_i$are unknown parameters. These parameters are measured using ANF signal extract the required signal to be injected at point of common coupling. The dynamics of the signal at the time of interface is given by second order differential equations as:

$$\ddot{x} + \theta^2 x = 2\zeta\theta e(t) \tag{4.25}$$

$$e(t) = u(t) - \dot{x} \tag{4.26}$$

$$\dot{\theta} = -\gamma\theta x e(t) \tag{4.27}$$

Here, $u(t)$is the input signal, θ represents the estimated frequency and ζ and γ are real and positive parameters, that determines the performance of ANF in terms of proper synchronization in phase and frequency for the injection of fundamental signal to the grid.

For extracting the fundamental component

$$u(t) = A_1 \sin(\omega_1 t + \delta) \tag{4.28}$$

Dynamics of the signal in eq. (2) has a periodic function in state equation in the form of

$$v(t) = \begin{pmatrix} x \\ \dot{x} \\ \theta \end{pmatrix} = \begin{pmatrix} -\frac{A_1}{\omega_1}\cos(\omega_1 + \delta) \\ A_1 \sin(\omega_1 + \delta) \\ \omega_1 \end{pmatrix} \tag{4.29}$$

The third entry of $v(t)$is the estimated frequency and it is identical to its correct value ω_1

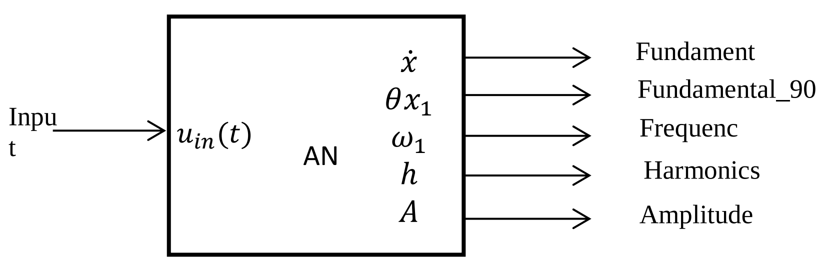


Figure 4.9 Basic Block of Adaptive Notch Filter

4.4 BATTERY CHARGING AND DISCHARGING

Battery is a storage device which is stores the excess power generated and uses it to supply the load in addition to the generators when power is required. Solar PV systems is integrated i.e. connected to a common DC bus of constant voltage and the battery bank is also connected to the DC bus. Any power transfer whether from generator to battery bank or generator to load or from the battery bank to the load takes place via this constant voltage DC bus. As the power flow associated with the battery is not unidirectional, a bidirectional converter is needed to charge and/or discharge the battery in case of excess and/or deficit of power respectively.

Bi-directional DC-DC converters are called so due to their ability of allowing the power flow in both the directions, depending on the requirement. There are many applications for the bidirectional converter such as Hybrid Vehicles, Uninterruptable Power Supplies (UPS) and also storage systems powered by Fuel cells and also renewable energy systems.

4.4.1 Classification of Bidirectional Converter

Based on the isolation between the input and output side, the bidirectional converters are classified into two types. They are

1. Non Isolated type
2. Isolated type

A basic non-isolated bidirectional converter can be derived from the unidirectional converters by using bi-directional switches. Basic buck and boost converters do not allow the bidirectional power flow due to the presence of the diodes that are unidirectional devices. This problem can be solved by using a MOSFET or IGBT with an anti-parallel diode which allows flow of current in both the directions.

The various non-isolated type bidirectional DC-DC converters are

1. Multilevel converter
2. Switched capacitor converter
3. Buck-Boost converter
4. Coupled inductor converter

The isolated type converters can operate in wide power ranges. The electrical isolation is achieved by using a power transformer in the circuit. But the transformer operates only for AC supply. Introducing AC link in the circuit increases the complexity of the circuit.

Based on the configuration, the isolated bidirectional DC-DC converters can be categorized into two types:

1. A current fed isolated bidirectional DC-DC converter
2. A voltage fed isolated bidirectional DC-DC converter

4.4.2 Bidirectional Converter for Battery Charging

As mentioned earlier, the bidirectional converter has many applications and here in the work, the converter is used for charging and discharging the battery based on the surplus and deficit of the power respectively.

When there is a surplus of energy, i.e. the supply is greater than demand then the battery is charged, allowing the converter to operate in forward direction. When there is a deficit in power i.e. the supply is less than demand then the battery starts discharging supplying the deficit of power to the load. This requires the converter to operate in reverse direction. Charging/discharging of the battery is done by the help of a bidirectional converter.

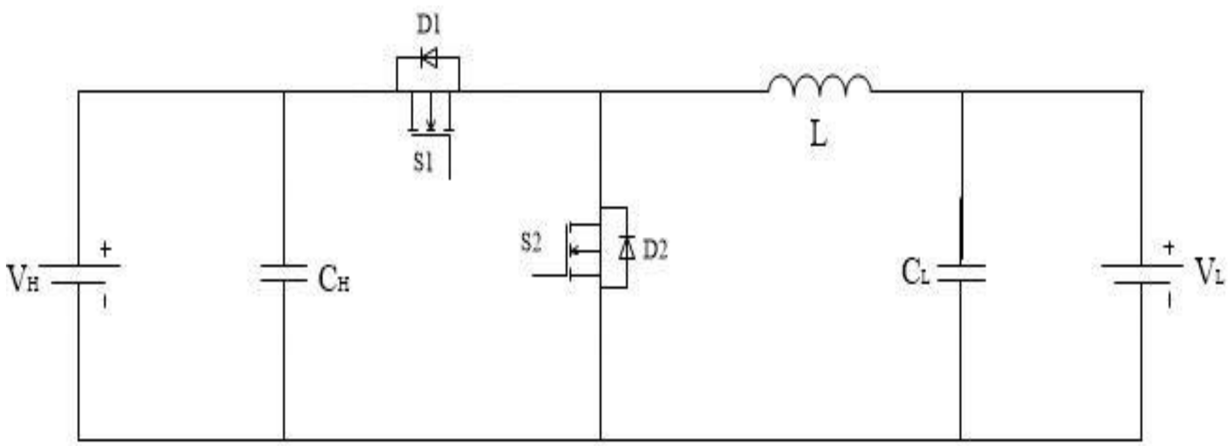


Figure 4.10 Circuit Diagram of Dual Converter

4.5 CONCLUSION

Different types of controller along with control algorithms for MPPT, inverter control and battery charging are discussed in this chapter

CHAPTER 5

DESIGN & MODELING OF THREE PHASE GRID CONNECTED SOLAR PV SYSTEM

5.1 INTRODUCTION

The downward tendency in the price of the photovoltaic modules, together with their increasing efficiency, put solid-state inverters under the spot lights as enabling technology for integrating PV systems into grid. Grid synchronization unit plays important role for grid connected SPV systems.

5.2 SYSTEM DESCRIPTION

The given system consists of a SPV array, DC/DC boost converter and a three phase voltage source converter with grid synchronization control schemes.

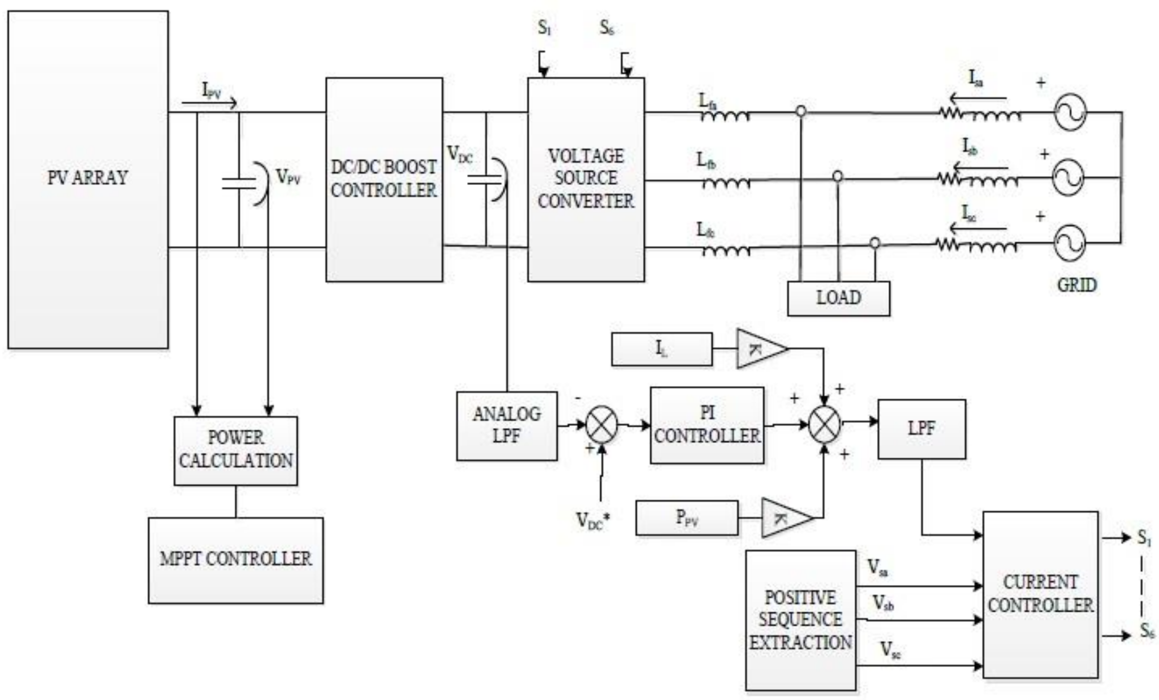


Figure 5.1 System Description

5.3 COMPONENT MODELING

The proposed system consists of various components like PV array, DC-DC converter and a three phase voltage source converter along it's with control algorithm. The present section describes the detailed modeling of each component of the given system.

5.3.1 PV Array Modeling

A single diode model has been considered to model the solar cell for this work. Equation based modeling of PV cell as well as PV module is presented in this section.

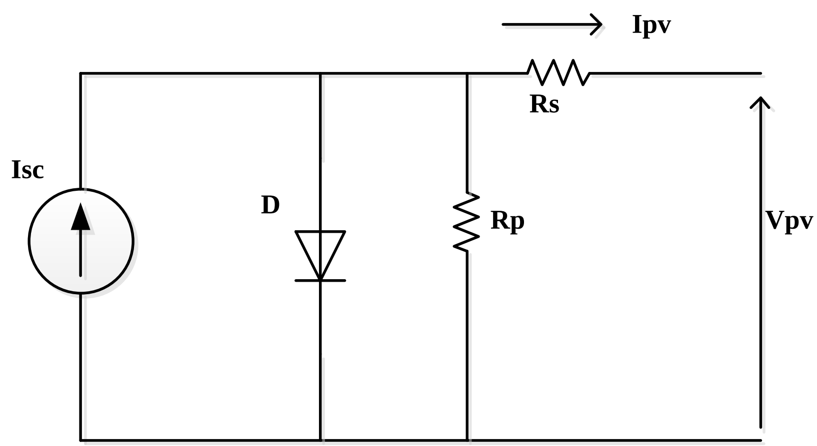


Figure 5.2 Equivalent Circuit Model of Solar Module

From the above circuit diagram, the I-V characteristics can be obtained by

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \tag{5.1}$$

Thus,

$$I_{PV} = I_{sc} - I_D - \frac{V_D}{R_p} \tag{5.2}$$

The reverse saturation current I_{rs} is given as

$$I_{rs} = I_{scref} + \left[\exp\left(\frac{qVoc}{NskAT}\right) - 1\right] \tag{5.3}$$

The module saturation current varies with the cell temperature is given by

$$I_o = I_{rs}\left[\frac{\left(\frac{T}{T_{ref}}\right)^3 e^{qCg}}{Ak} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (5.4)$$

The basic equation that describes the current output of the PV module of the single-diode model is given in equation (5.5).

$$I_{PV} = I_{sc}N_p - N_s I_o\left[\exp\left\{\frac{q(V_{PV}+I_{PV}Rs)}{N_s AkT}\right\} - 1\right]V_{PV} + \frac{I_{PV}Rs}{Rp} \quad (5.5)$$

Where k is the Boltzmann constant (1.38 x 10^{-23} J K^{-1}), q is the electronic charge (1.602 x 10^{-19} C), T is the cell temperature (K); A is the diode ideality factor, R_s the series resistance (Ω) and R_p is the shunt resistance (Ω). N_S is the number of cells connected in series = 36. N_p is the number of cells connected in parallel = 1. The MATLAB Simulation of Solar PV panel is shown in the Figure 5.3

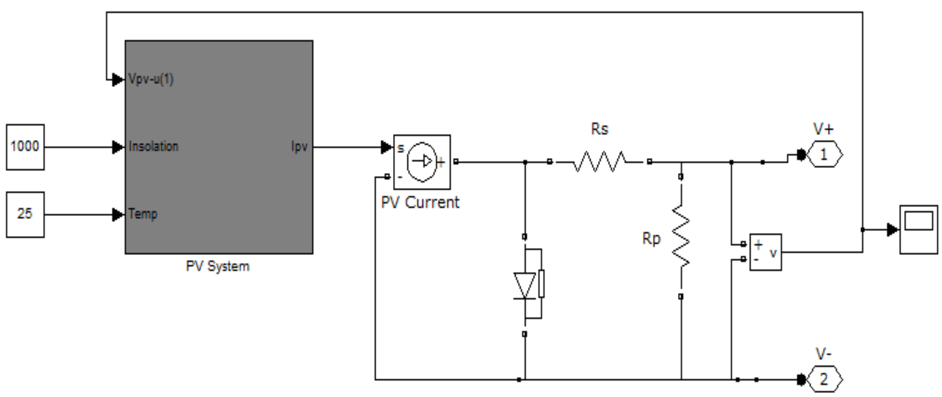


Figure 5.3 MATLAB Simulation of Solar PV Panel

5.3.2 DC/DC Boost Converter Modeling

Output of PV array is highly affected by the meteorological parameters like irradiance, temperature and keeps on changing. A control technique named as MPPT (maximum power point tracking) is required to continuously track the maximum power point of PV array. A power converter is required to implement the MPPT control and to step up the voltage level at a value so that the DC link voltage can be maintained at a constant value.

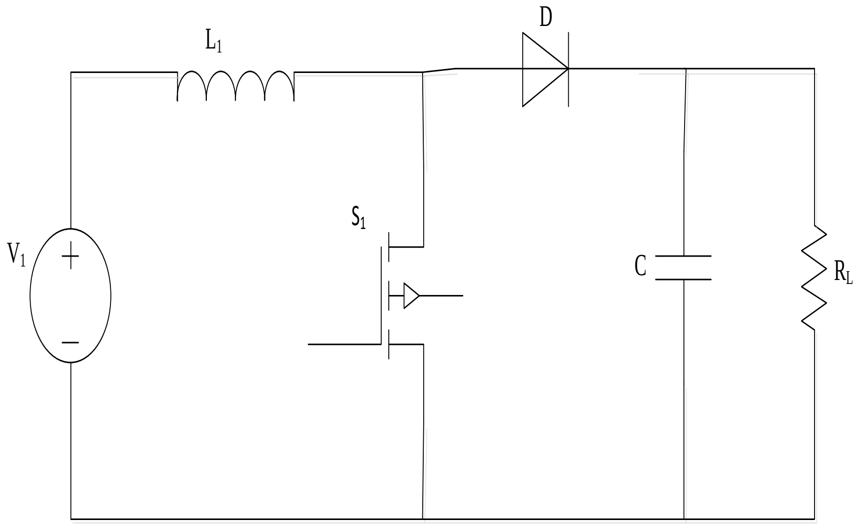


Figure 5.4 Equivalent Circuit Model of DC/DC Boost Converter

Table 5.1 Parameter Calculations for DC/DC Boost Converter

Parameter	Formula	Value
PV Output voltage (V_{PV})	-	650 V
Switching Frequency (f_{sw})	-	10.6kHz
Duty Cycle (D)	$\text{D} = 1 - \frac{V_{PV}}{V_{DC}}$	0.375
Input Inductance (L_1)	$L_1 = \frac{V_{PV}\ \text{D}}{2\Delta i_1 f_{sw}}$	1.5 mH
DC link Capacitors (C)	$C = \frac{I_{in}\text{D}}{\Delta v f_{sw}}$	2800µF

Where,

I_{in}= Input current to DC/DC boost converter

Δi_1 = Input Current ripple (about 10%)

Δv = Input voltage ripple (3 %)

5.3.3 Voltage Source Converter Modeling

The three phase voltage source converter consists of a six switching devices which converts DC voltage into AC voltage. The VSC consists of capacitors to filter the DC link voltage. In the VSC, IGBT semiconductor switches are used and designed for 415 V, 25 kW at 0.8 p.f. lagging load. Figure 5.5 shows a circuit representation of three phase voltage source converter.

Table 5.2 Parameter Calculations for Voltage Source Converter

Parameter	**Formula**	**Value**
RMS Load current (I_{RMS})	$\frac{\text{VA}}{3V_o}$	25 A
Switching Frequency (f_{sw})	-	10kHz

Where,

VA= Load Power/Power factor

V_o = Output voltage (Line to line)

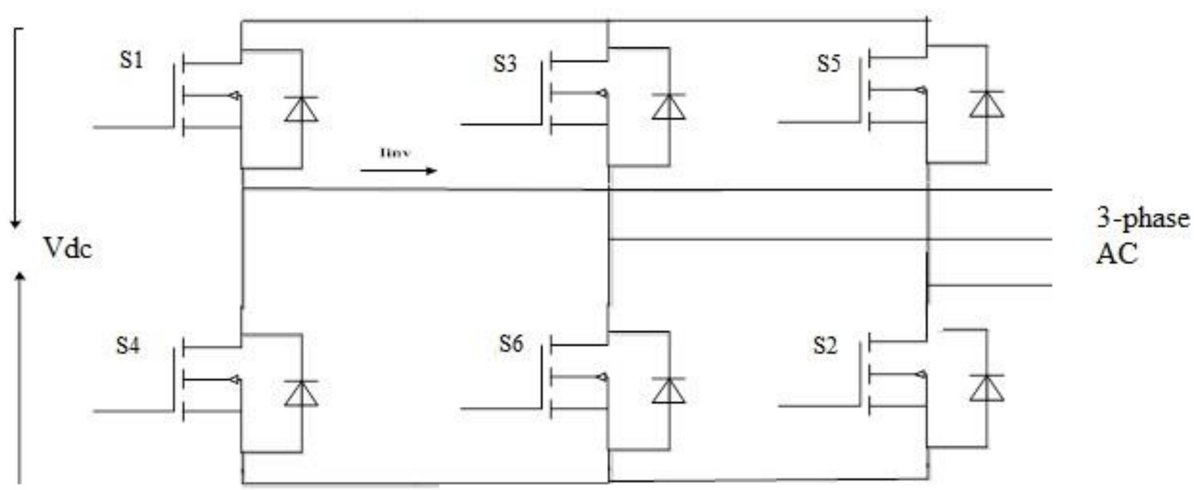


Figure 5.5 Circuit Diagram of Voltage Source Inverter (VSI)

5.3.4 MPPT Controller

Perturb and observe method for tracking the maximum power point of solar PV array is implemented here. After the application of perturbation the output power is compared with the previous perturbation cycle power output. If the power increases then the increment in voltage or current remains continuous in same direction. If power decreases then the variation in voltage or current in reverse direction. A flowchart illustrating the operation of this method is shown in Figure 5.5.

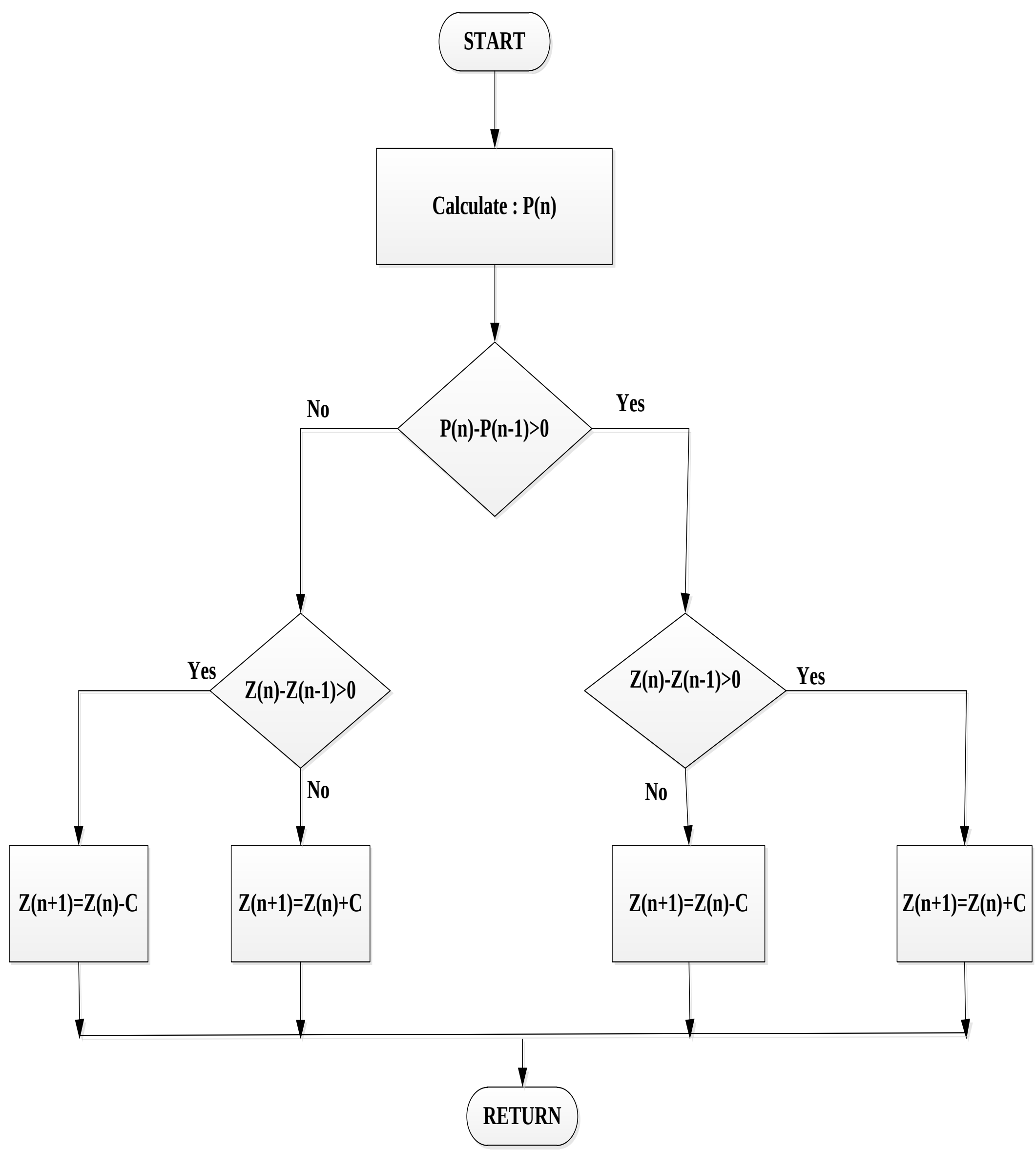


Figure 5.6 Flowchart for Perturb & Observe MPPT Technique

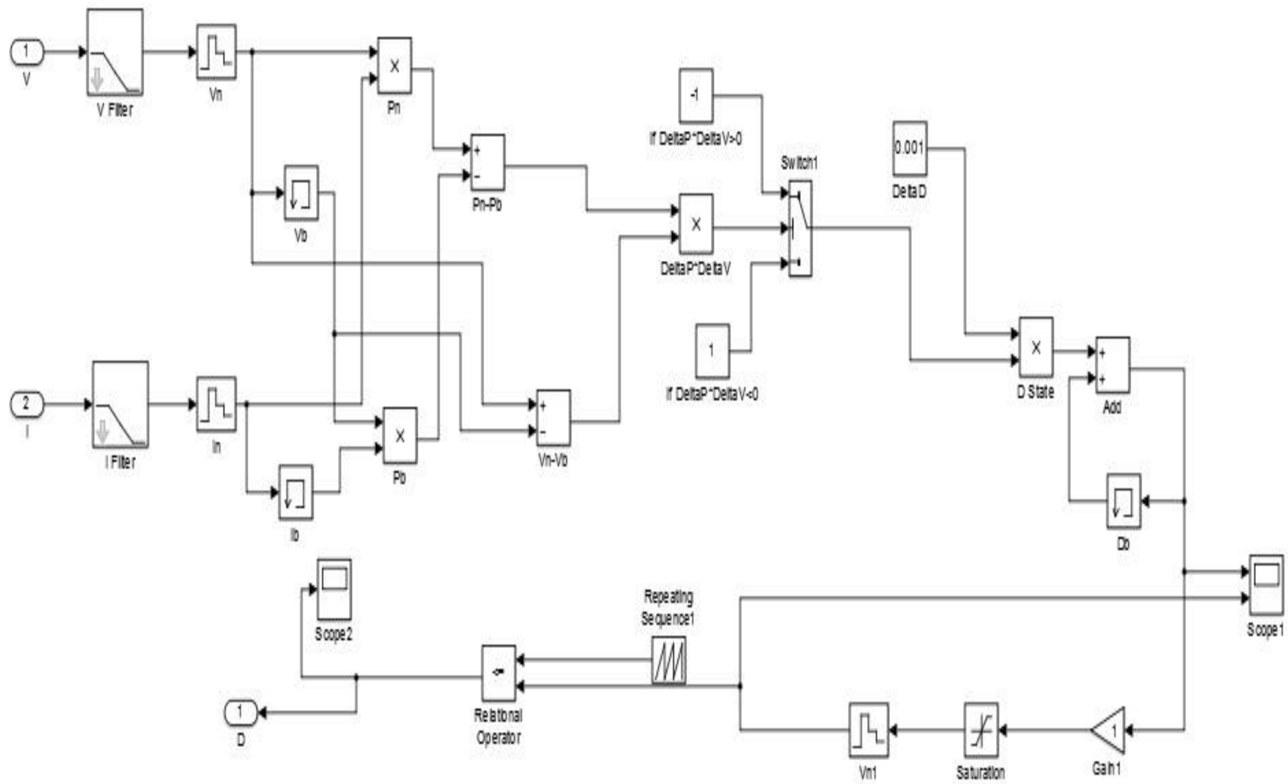


Figure 5.7 MATLAB Simulation of P&O MPPT Controller

5.3.5 Inverter Controller

DC-AC stage must only inject active component of grid current. So for this the steady state current error between the actual and desired grid current should remain zero at any grid frequency. Phase locked loop (PLL) tracks the phase of input voltage signal and generate unit voltage templates (sine and cosine components). The d-q components of currents passed by a filter which filter out high frequency harmonic components. Then again d-q frame is transformed back to 3-phase components. This current is then compared with source current and error between them is fed to Hysteresis-based PWM signal generator to produce final switching signals which are the pulses for inverter.

System terminal voltages are given as,

$$v_\alpha = V_m \cos(\omega t + \Phi) \tag{5.6}$$

And current are given as:

$$i_\alpha = I_m \cos(\omega t + \theta_n) \tag{5.7}$$

Following equation gives

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{5.8}$$

i_d= In phase component of Grid current

i_q= Reactive component of Grid current

$$\begin{bmatrix} i_d = I\cos(\Phi - \theta_n) \\ i_q = -I\sin(\Phi - \theta_n) \end{bmatrix} \tag{5.9}$$

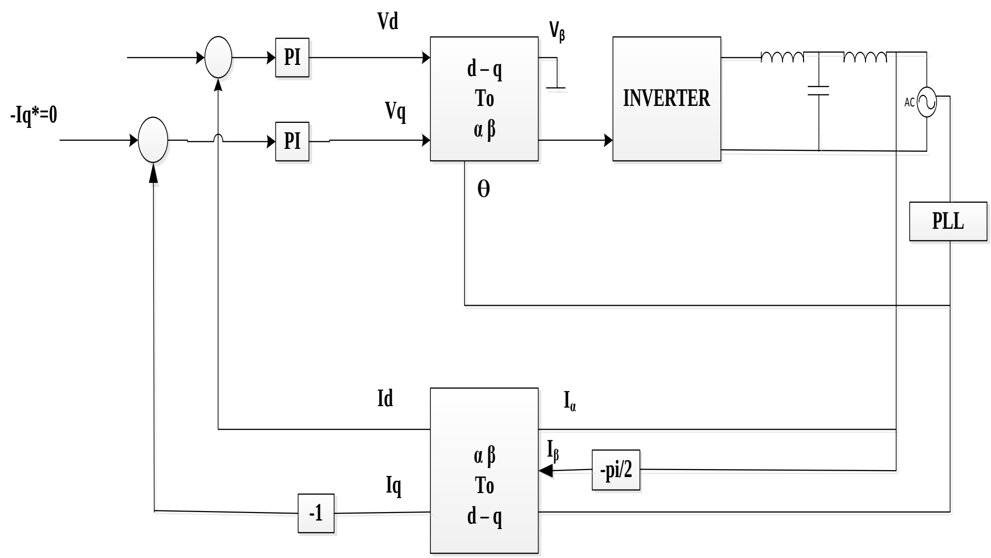


Figure 5.8 Reference Current Extraction using SRF Theory

These reference currents are compared with actual current and error between both will be the required amount of reactive current supplied by inverter. Error of current is used to generate pulses for inverter. The MATLAB Simulation of SRF based

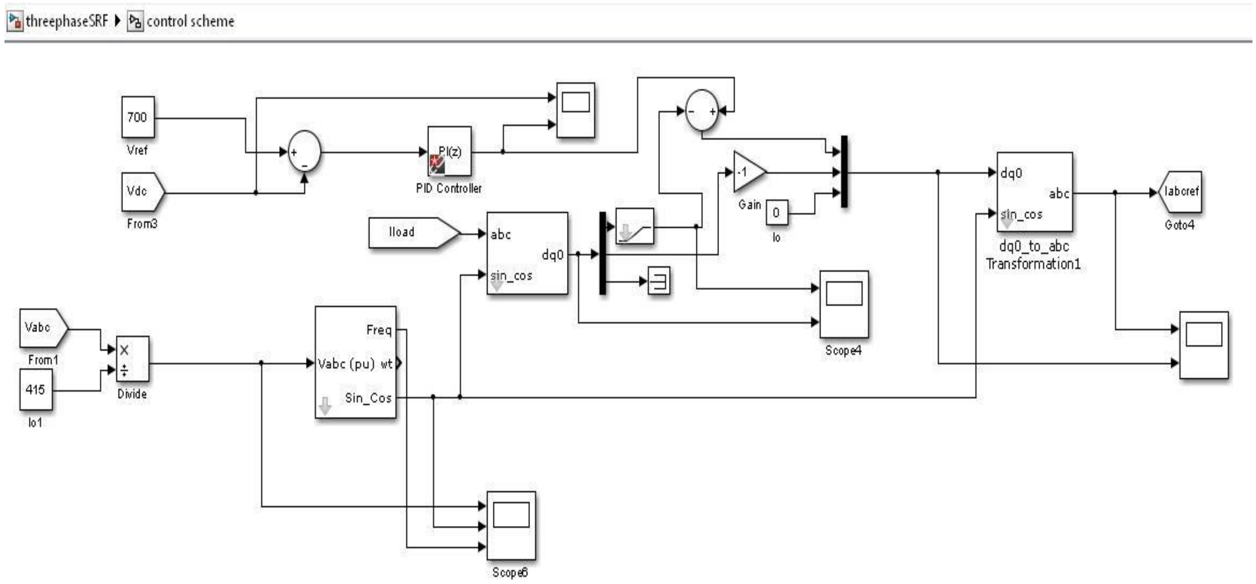


Figure 5.9 MATLAB Simulation of SRF Control Scheme for Grid Synchronization

5.3.6 Connected Load

There are different types of load connected to a grid. They can be classified in various categories according to various factors such as nature of load, load function, load operation time, load phases etc.

In this dissertation load connected to the 3 phase grid connected solar PV system is of following type

1. Continuous connected load- A three phase balanced lagging load of 50 KVA is always connected to the system
2. Non-linear load- A single phase diode bridge connected lagging load is also connected.
3. Discontinuous load- A three phase balanced load is connected through circuit breaker which is at times applied to the system.

Now, the MATLAB simulated model of a 3-phase grid connected system is shown in the Figure 5.10 which incorporate a PV array connected to a DC-DC boost converter, a DC to AC three phase voltage source inverter, a three phase 415 V grid with the above mentioned load connected at PCC point.

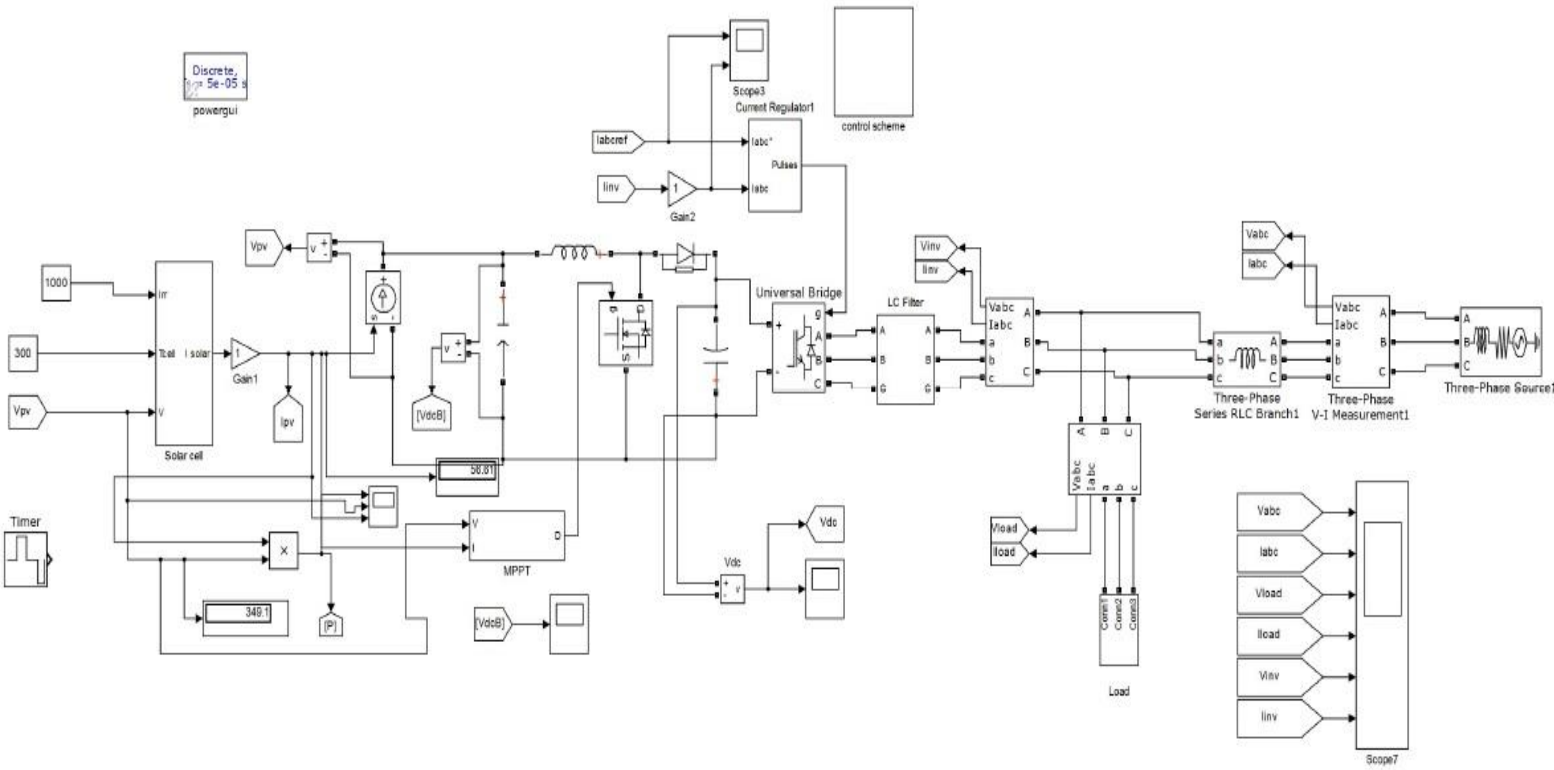


Figure 5.10 MATLAB Simulation of Grid Connected Solar PV

5.4 CONCLUSION

This chapter presents the MATLAB simulation model of three phase grid connected solar PV system along with MATLAB models of solar PV Panels, DC-DC boost converters, DC-AC inverters, MPPT Algorithm, inverter control algorithm etc.

CHAPTER 6

RESULTS & DISCUSSIONS

6.1 INDRODUCTION

The performance of three phase grid connected solar PV System is analysed for different kind of loads. Also the impacts of changing meteorological parameters specially irradiance is studied. Impacts of increasing percentage penetration of solar PV on the existing grid is also analysed through THD and voltage at the PCC point.

6.2 PERFORMANCE OF THREE PHASE GRID CONNECTED SYSTEM

A 5 KW grid connected solar PV system MATLAB model is simulated as shown in the previous chapter. Its performance is analysed by observing the various parameters like dc power supplied by solar PV system, dc link voltage, 3phase voltage and active & reactive power supplied by the system etc. at constant irradiance and at changing irradiance

6.2.1 DC Power Supplied by the Solar PV System

Power supplied by solar PV system is dependent on the voltage and the current of solar panel which in turn dependent on the irradiance and temperature. At constant ambient temperature DC power supplied by solar pv panel follows the irradiance pattern. This can be shown by the Figures 6.1 and Figure 6.2.

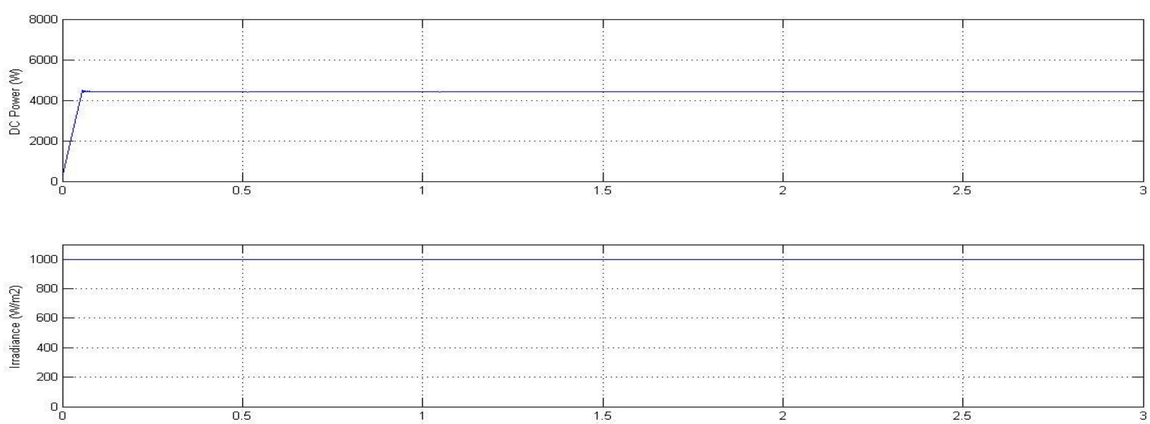


Figure 6.1 DC Power of Solar PV System at Constant Irradiance

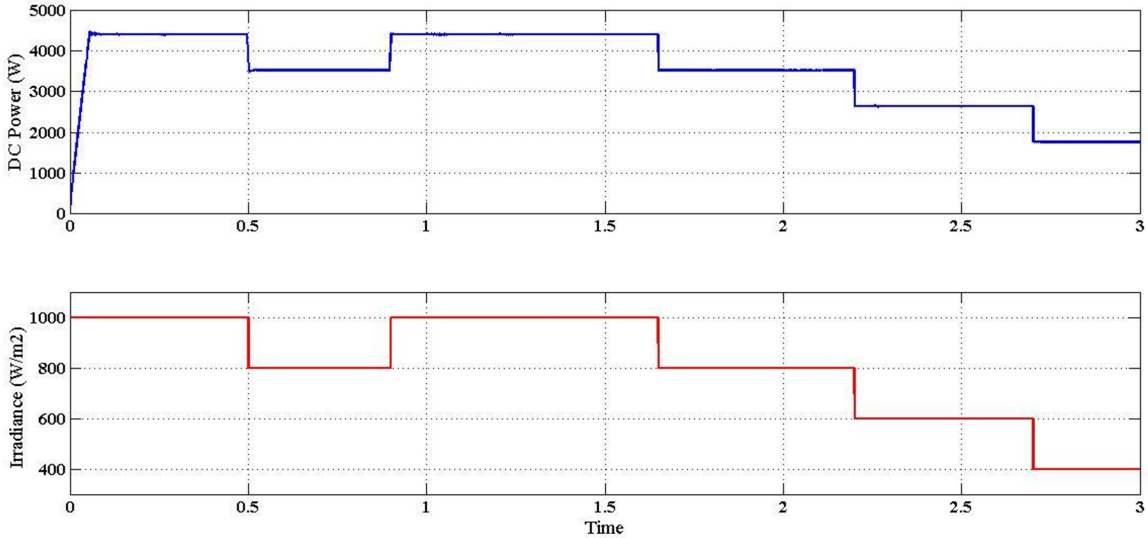


Figure 6.2 DC Power of Solar PV System at varying irradiance

6.2.2 PV Voltage and Current

Solar PV voltage and current is very important parameter for the performance of solar PV system. These are the parameters which are used as input to MPPT control which in turn generate pulses for DC-DC boost converter. As mentioned in the previous chapters that PV voltage does not vary much due to change of irradiance but current is purely dependent on the irradiance pattern this is shown in the Figure 6.3.

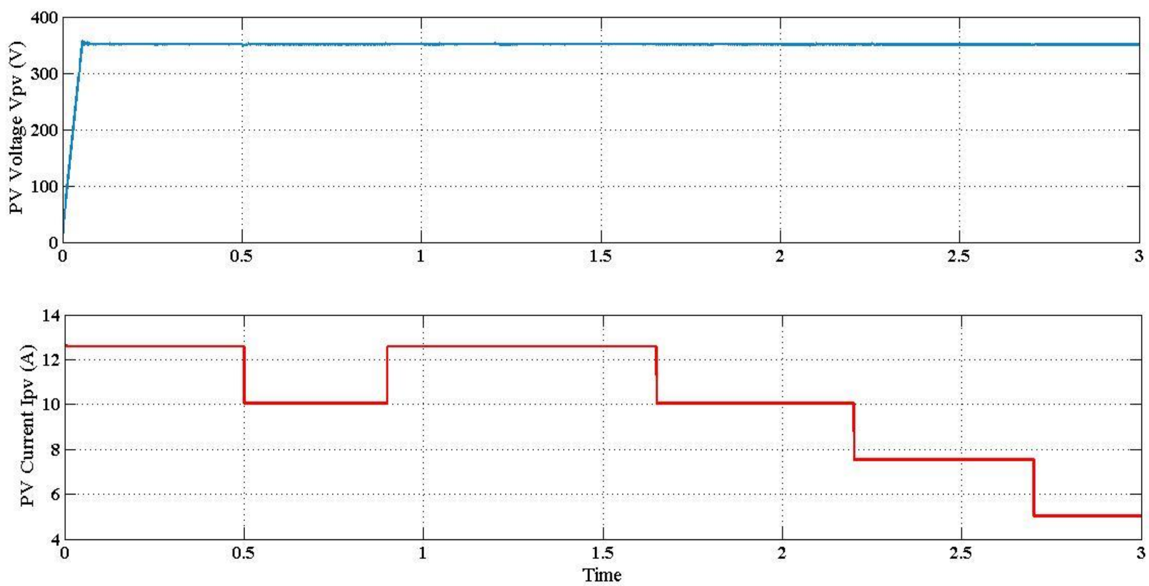


Figure 6.3 PV Voltage and Current

6.2.3 DC Link Voltage

DC link voltage is the voltage that is applied to the inverter input. A DC-DC converter is used to maintain dc link voltage of desired value. A high value capacitor is used to maintain the DC link voltage constant. An almost constant 700 V DC link is obtained from boost converter. This can be shown in the Figure 6.4

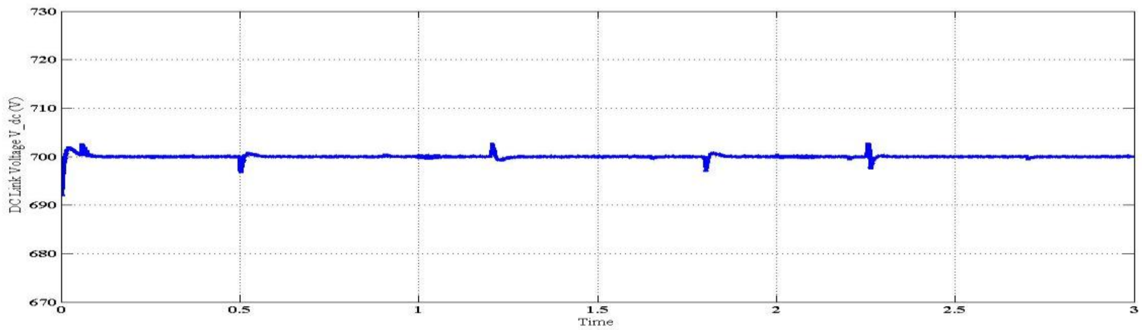


Figure 6.4 DC link voltage

6.2.4 Inverter Voltage and Current

Inverter (VSI) produces a three phase ac voltage output to supply the three phase load at PCC point. A three phase universal bridge utilising IGBT switch is used in MATLAB simulation work to convert DC link voltage to three phase ac. Pulses for IGBT switches is produced by inverter control block. The three phase balanced voltage and current supplied by inverter is shown in the Figure 6.5. As VSI uses solid state switches which produces current harmonics that can be clearly shown in the Figure 6.5.

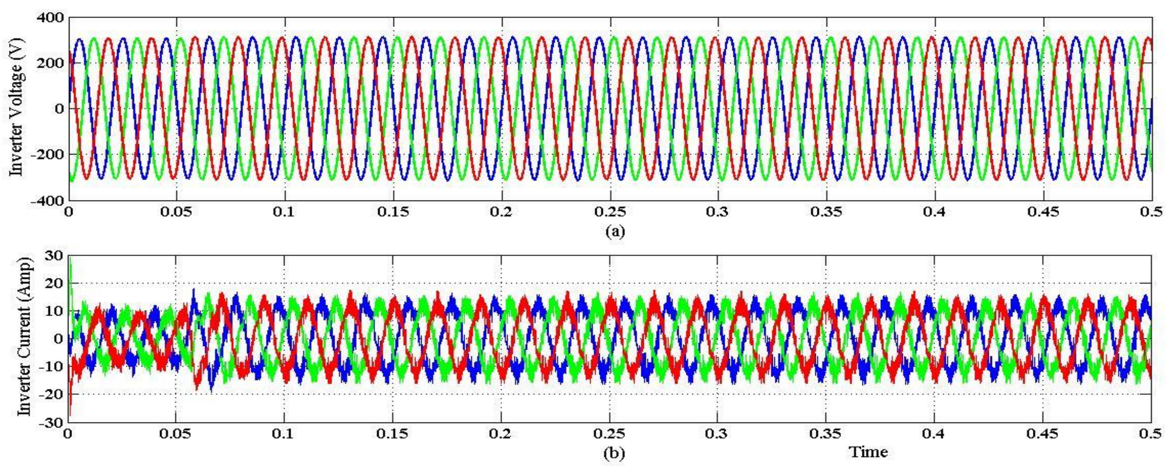


Figure 6.5 Inverter (a) voltage (b) Current

6.2.5 Power Supplied to Grid

Active power and reactive power both are supplied by the system. As shown in the Figure 6.6 and Figure 6.7 the active power is dependent on the irradiance parameter and the almost constant reactive power is supplied irrespective of the meteorological parameter variation. Only the partial requirement of reactive power is supplied by solar PV system.

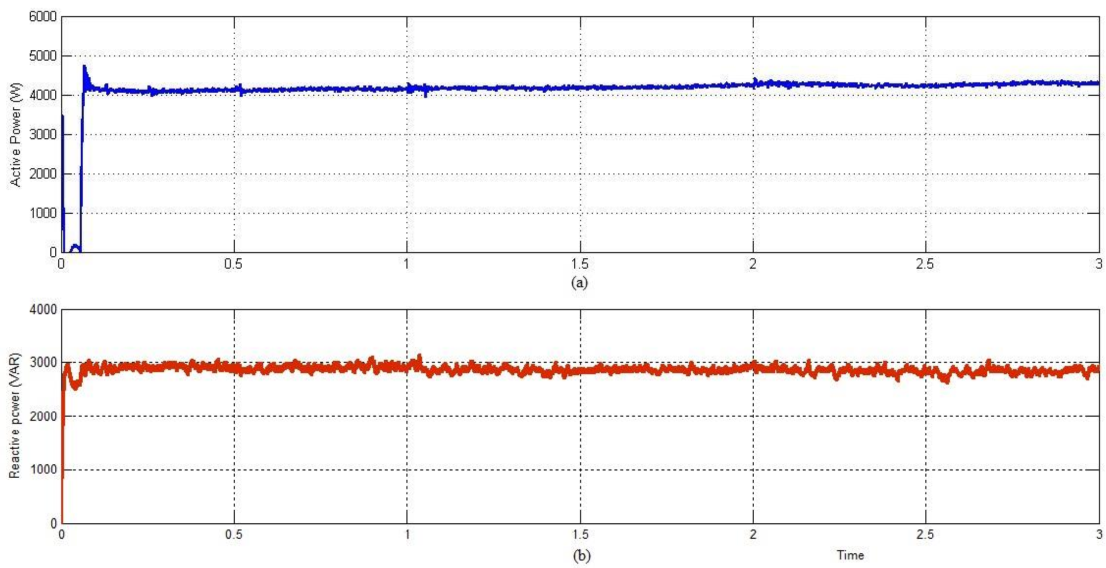


Figure 6.6 Power supplied to grid at constant irradiance a) Active power b) Reactive power

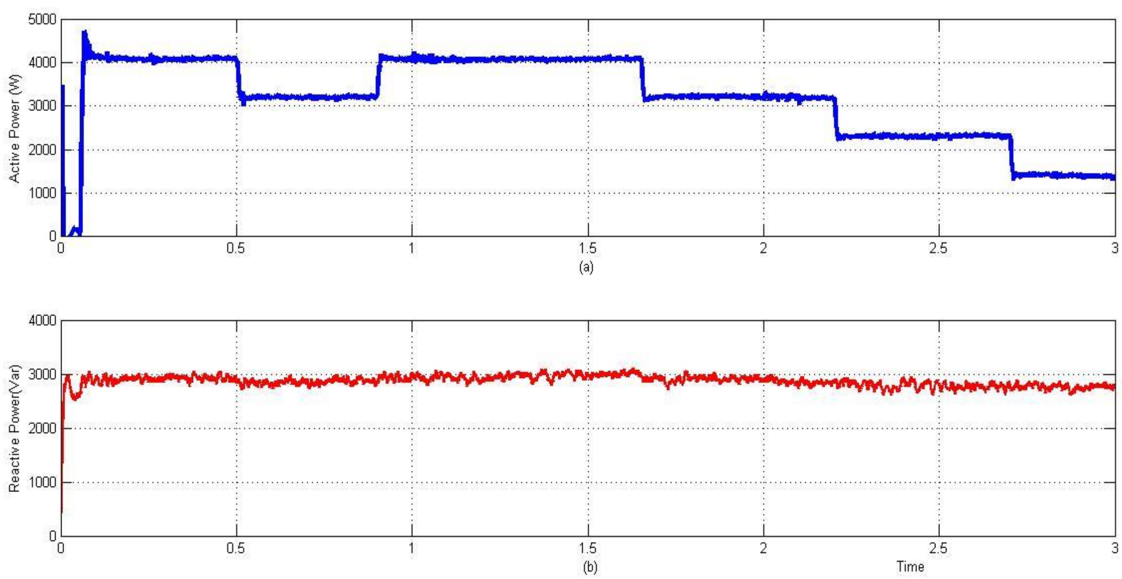


Figure 6.7 Power Supplied to Grid at Varying Irradiance a) Active power b) Reactive power

6.3 POWER QUALITY ANALYSIS OF SYSTEM

Power quality of a grid connected solar PV system can be analysed by the PCC point voltage analysis for different kinds of loads and for changing meteorological conditions, harmonic distortion in voltage at PCC point and harmonic distortion in current in the grid for different levels of percentage penetration.

6.3.1 Harmonic Analysis of Grid

As grid integration of solar PV system requires DC-DC Converter and three phase VSI which utilise many power electronics switches which in turn produced harmonics in the system. Hence, harmonic analysis is important for grid integrated system. However, a VSI is used as inverter and a synchronous reference frame theory is used to extract reference current for inverter control hence voltage generated is almost balanced while the current harmonics is very high in the system.

Now as the percentage penetration level of solar PV system increases in the grid the more and more current harmonics are introduced in the grid. Initially grid current is same as load current with harmonics 0.51% as penetration level increases up-to 30% the current harmonics of grid also increases to 5.18% which is beyond standard permissible limit of 5%. This can be shown by the Figure 6.8 and Figure 6.9.

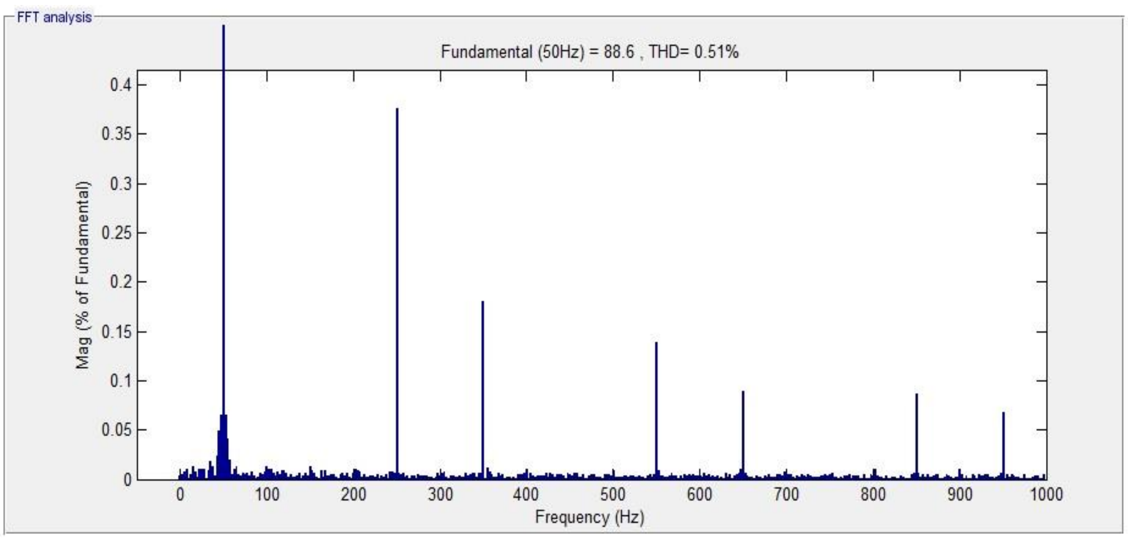
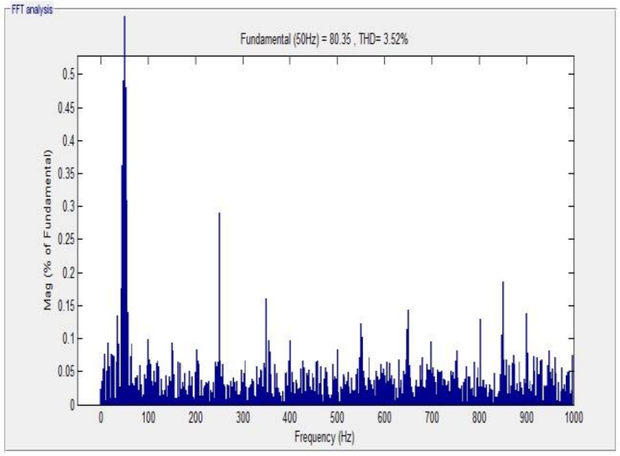
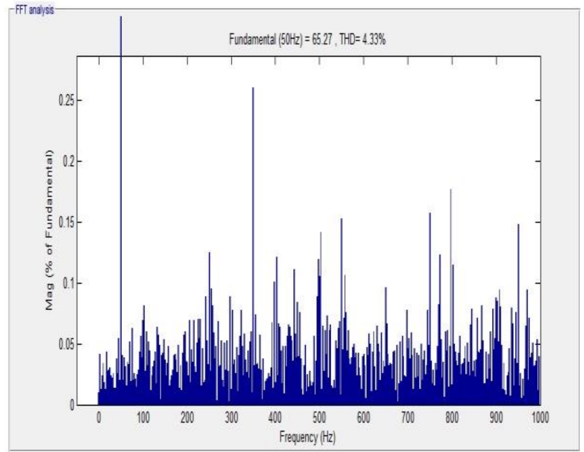
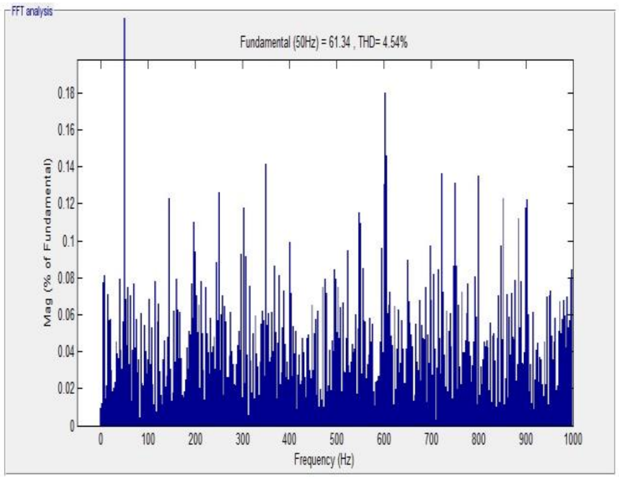


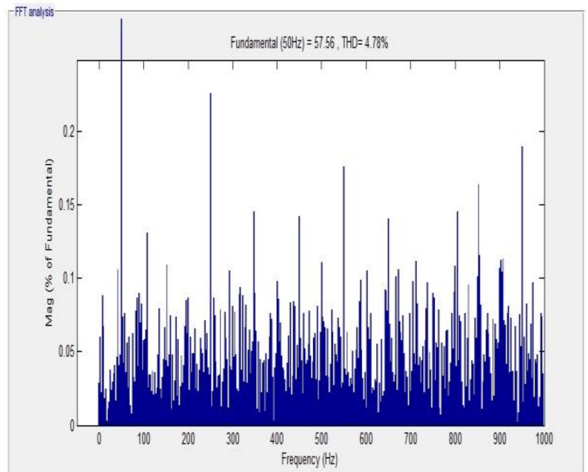
Figure 6.8 THD of Load Current



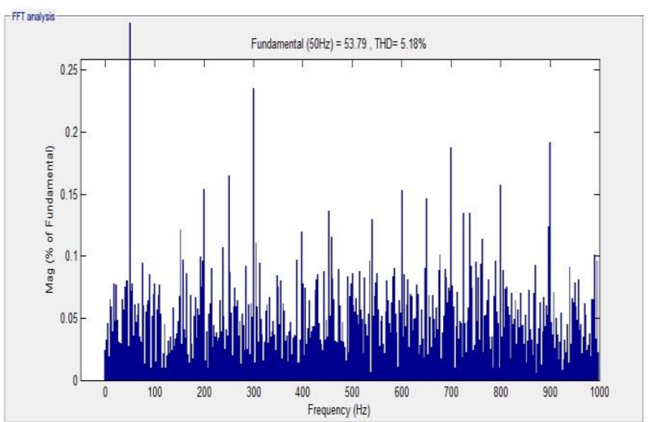


(a) **(b)**





(c) **(d)**



(e)

Figure 6.9 Percentage Current THD of Grid at (a) 10% (b) 15% (c) 20% (d) 25% (e) 30% PV Penetration

6.3.2 PCC Point Voltage Variation

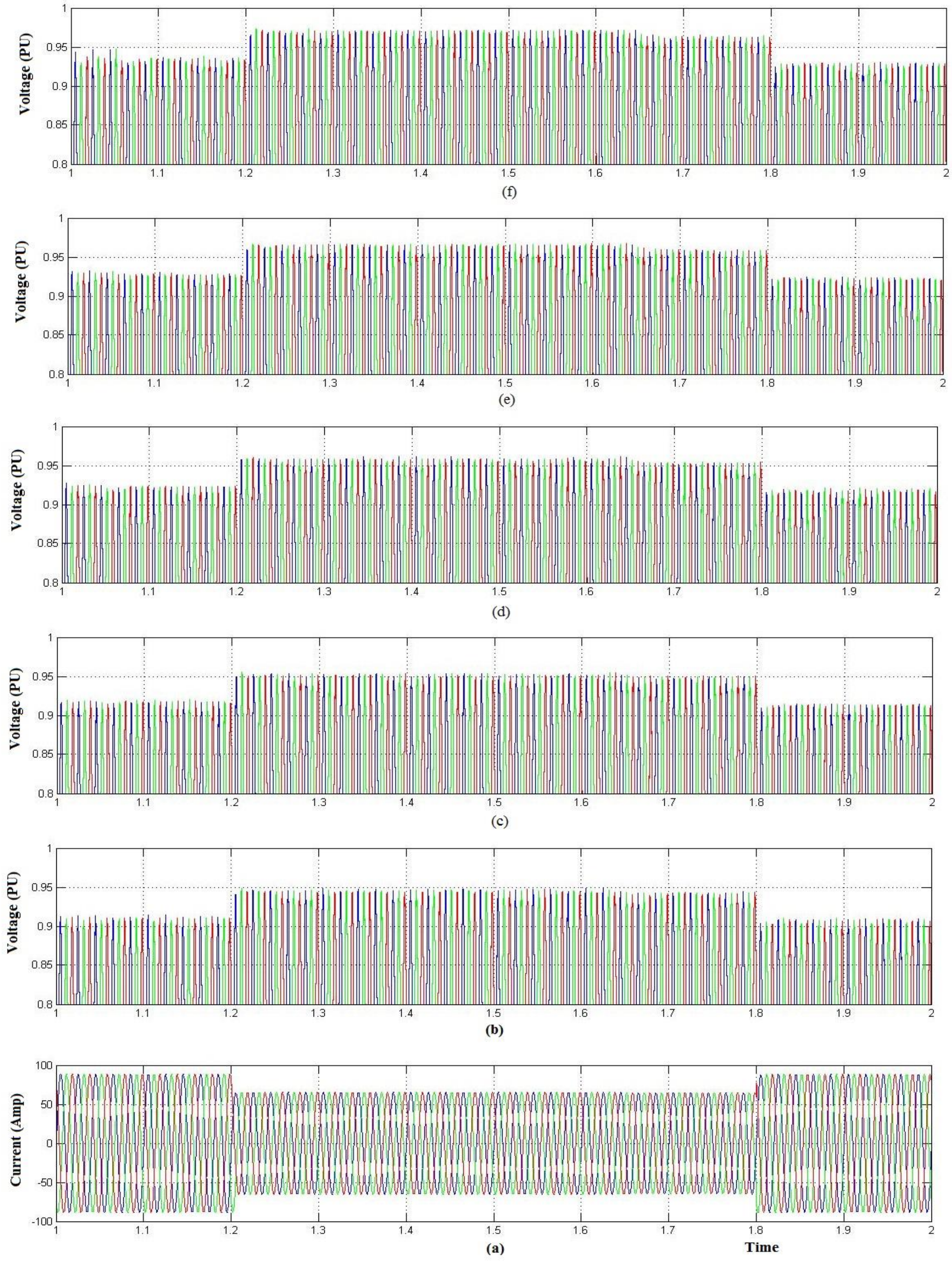


Figure 6.10 (a) Discontinuous Load Current and Voltage fluctuation levels at (b) 10% (c) 15% (d) 20% (e) 25% (f) 30%

6.4 CONCLUSION

In this chapter results of MATLAB simulated three phase grid connected solar PV system is discussed. Power, voltage and current produced by solar PV at constant and varying irradiance conditions, dc link voltage after applying P&O MPPT technique and active and reactive power supplied by inverter due to inverter control is presented and are satisfactory.

Also, power quality analysis of three phase grid connected system is presented when the percentage penetration of solar PV increased from 10% to 30% on the basis of harmonic distortion in the current of grid and voltage at the PCC point. The same comparison is given in the table 6.1

Table 6.1 Comparison of power quality at different percentage penetration

% Penetration of SPV	% Current THD of Grid	% Voltage THD of PCC Point
0	0.5	0.2
10	3.52	1.5
15	4.33	1.4
20	4.54	1.31
25	4.78	1.27
30	5.18	1.22

CHAPTER 7

CONCLUSION & FUTURE SCOPE

7.1 INTRODUCTION

After discussing about the various aspects of this dissertation from conceptualization to design and results, the next most important thing is to draw the conclusions from this research work. This chapter discusses the conclusions arrived and also outline the scope for future work in this area.

7.2 CONCLUSION

The objective of this dissertation is to develop a three phase grid connected solar PV system with different types of loads such as linear, non-linear and discontinuous. Also analyse the performance of this system to constant and changing irradiance levels and power quality analysis of the PCC point and then study the effect on grid current harmonic distortion when the percentage penetration of solar PV system in the grid system increases from 10% to 30%. All the objective have been met successfully.

Performance analysis of three phase grid connected system with P&O MPPT technique and inverter control scheme bases on synchronous reference frame theory is carried out. The performance of solar PV system is analysed for constant and different levels of irradiance on the basis of Vpv, Ipv, Vdc, power supplied by solar panel and active and reactive power supplied by the inverter.

Further power quality three phase grid connected system is analysed on the basis of variation of PCC point voltage at the discontinuous load and total harmonic distortion (THD) analysis of the grid current for increasing percentage penetration of Solar PV in the existing grid. As distribution grid is weak grid i.e. high R/X ratio PCC point voltage is effected by sudden load change or change in irradiance which directly affect the active power supplied by the Solar PV. Also, to connect solar PV system with grid many power electronic switches is used which produces harmonics, hence THD level of grid current goes on increases from 3.52% to 5.18% as the percentage penetration increases from 10% to 30% .

7.3 FUTURE SCOPE

The present work can also be extended in future.

- The hardware can be developed for grid connected 3 phase Solar PV systems.
- After developing the hardware, power quality analysis of grid connected PV systems can be carried out.
- Further, the Solar PV system can also be integrate with a DSTATCOM for complete reactive power compensation.
- Also, the grid integrated Solar PV systems are integrated with filters (passive or hybrid filters) to contain the harmonic level of existing grid to prescribed value as per power quality standards.

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