MODELLING, SIMULATION AND HARDWARE IMPLEMENTATION OF SPV SYSTEM WITH MPPT ALGORITHMS

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I, **Priyanka Chaudhary**, Roll No. 2K12/PSY/17 student of **M. Tech. (Power System)**, hereby declare that the dissertation titled **"Modeling, Simulation and Hardware Implementation of SPV System with MPPT Algorithms"** under the supervision of Dr. M. Rizwan, Assistant Professor, Department of Electrical Engineering, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

Solar photovoltaic (PV) technology is becoming more popular because of number of advantages. These advantages include zero green house emission, low maintenance cost, least limitations with regard to site installation. However, the conversion efficiency of PV technology is very low about 15-18%. Also, the power generated from PV system is varying with meteorological parameters like solar irradiance, temperature etc.

It is very important to analyse the performance of PV system under different meteorological conditions and also track the maximum power point (MPP) using MPPT technique. By keeping in the aforesaid a performance analysis of perturb and observe (P & O), incremental conductance and constant voltage MPPT techniques have been analysed and carried out in this research.

When light falls on solar panel it produces a DC voltage, this can be directly used for DC applications or can be converted to AC by using an inverter that is then applied directly to the commercial electrical grid or to a local, off-grid electrical network.

Second objective of this work is to design and develop a single phase grid connected PV system with different control algorithms. A three phase grid connected system also designed and developed with adaptive notch filter based grid synchronization technique for providing active and reactive power to the load and utility grid. A lab scale hardware setup is also developed with solar panel, boost converter and inverter for the purpose of performance analysis of various MPPT techniques and developed control schemes of single phase H bridge inverter.

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

The purpose of this chapter is to present the motivation behind the work done in this thesis. The chapter also provides the main objectives of the research as well as the thesis organization.

1.2 MOTIVATION

The demand for electric energy is expected to increase rapidly due to the global population growth and industrialization in the near future. This 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 December 31, 2013 was 234456 MW and with per capita energy consumption of 917 kWh as on March 2013 [1]. 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 December 2013, the current installed capacity of thermal power is 159794 MW which is 68% of total installed capacity. Current installed capacity of coal based thermal power is 138213 MW which comes to 59% of total installed base and current installed base of gas based thermal power is 20382 MW which is 9% of total installed base, while oil based thermal power is 1,200 MW which is 0.5% of total installed base. In addition, 39893 MW of power is generated through large hydro and 4780 MW and 29989 MW of power is generated from nuclear energy and renewable energyresources respectively. The graphical representation of Indian power sector as on December 31, 2013 is presented in Fig. 1.1.

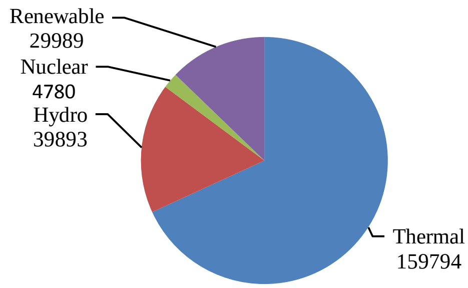


Fig. 1.1 Indian power sector at glance (MW)

As renewable energy is concerned, the current installed base of renewable energy is 29989 MW. The power generation through wind is 20150 MW; small hydro contributes 3763 MW while the power generated from biomass and solar photovoltaic technology is 3896 MW and 2180 MW respectively [1]. 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 December, 2013 is shown in Fig. 1.2.

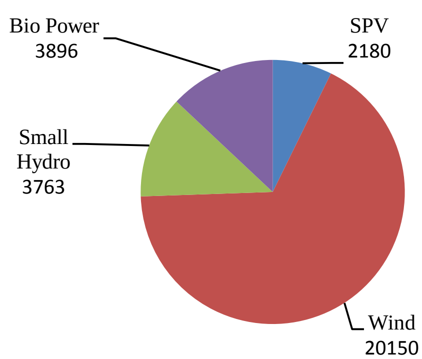


Fig. 1.2 Contribution of RES in Indian Power Sector (MW)

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 theyown the advantage of being maintenance and pollution free. In the past few years, solarenergy sources demand has grown consistently due to the following factors:

1) Increasingefficiency of solar cells

2) Manufacturing technology improvement and

3) Economies ofscale.

Meanwhile, more and more PV modules have been and will be connected to utilitygrid in many countries. Now the largest PV power plant is more than 100MW all over theworld. Furthermore, the output of PV arrays is influenced by solar irradiation andweather 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, and 3) on-grid, or grid connected applications, in which solar arrays are used to supply energy to local loads as well as to the electric 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 2022 under Jawaharlal Nehru National Solar Mission (JNNSM) [1]. This will change the scenario significantly.

1.3 SCOPE OF WORK

The power generated from PV system is varying with meteorological parameters like solar irradiance, temperature etc. Therefore, it is important to analyse the performance of PV system under different meteorological conditions and also track the maximum power point (MPP) using MPPT technique.Also the PV systems have very low overall efficiency about 13-20% as they suffer from many conversion losses. Hence this thesis is aimed to develop, analyzeand study the simulation and hardware model of the solar PV system with MPPTfor improving the efficiency and performance. The main objective of this work is

- To design and develop MATLAB/Simulink model of Solar Photo Voltaic (SPV) system
- Performance analysis of Maximum Power Point Tracking (MPPT) techniques for PV system with battery storage
- To develop the simulation model and hardware setup for single phase solar PV system with actual PV module for grid integration with various control schemes
- To develop the simulation model three phase solar PV system with actual PV module for grid integration with various control schemes

1.4 ORGANIZATION OF THESIS

CHAPTER 2 - This chapter consists of the literature survey on Solar PV technologies, DC/DC converter, MPPT techniques, PWM inverter, single phase grid connected PV systems and three phase grid connected PV systems.

CHAPTER 3 - This chapter deals with the theoretical information regarding the use of solar PV technology.

CHAPTER 4 - 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 - This chapter consists of design, modeling and simulation of a single phase grid connected PV system with various control schemes.

CHAPTER 6 - This chapter presents design, modeling and simulation of a three phase grid connected PV system with various control schemes.

CHAPTER 7 - Hardware Implementation

CHAPTER 8 - This chapter presents result and discussions.

CHAPTER 9 - This chapter brings out the main conclusion of this research work 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, grid connected PV inverter topologies, power quality issues with grid connected PV systems have been studied, which form the back bone of the present work.

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. 2180 MW as on 31st December 2013 [1].

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 CdTe. The monocrystalline cell has the highest efficiency.

2.3MODELING, 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 [2-10]. 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 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 simpowersytem block of MATLAB/Simulink. This paper also presented the MPDT control with DC/DC boost converter with appropriate simulation results.

M. Abdulkadir et.al 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 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.

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

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 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

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

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

There are seven parameters I_{PV}, I_{O1}, I_{O2}, R_P, R_S, a_1, a_2 for simplicity researchers assumed that α_1=1, α_2=2. Further authors modified the output current equation for PV array as

$$I = N_{PP}I_{PV} - I_{o1}N_{PP}\left[\exp\left\{\frac{V+IR_S\left(\frac{N_{PP}}{N_{SS}}\right)}{\alpha_1 V_{T1}N_{SS}}\right\} - 1\right] - I_{o2}\left[\exp\left\{\frac{V+IR_S\left(\frac{N_{PP}}{N_{SS}}\right)}{\alpha_2 V_{T2}N_{SS}}\right\} - 1\right] - \left\{\frac{V+IR_S\left(\frac{N_{PP}}{N_{SS}}\right)}{R_P\left(\frac{N_{PP}}{N_{SS}}\right)}\right\} \quad (2.3)$$

J.A Gow et.al 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.

2.4POWER 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, flyback, buck-boost etc [11-14, 51, 65-67, 88-89]. The choice of topology depends on system requirements and its applications.

Ahmed H. El Khateb et. al [14] 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.

Amudhavalli D. et.al [11] 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.

Yungtaek Jang et.al [12] 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.

Hyuntae Choi et.al [10] 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 analyzed for three different cases.

1. Constant solar irradiance.
2. Fast changing irradiance.

3. Grid voltage sag.

Proposed configuration allows the PV system to achieve medium voltage levels without need of a low voltage step up transformer.

T.Shanti et.al [13] 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.

2.5MAXIMUM 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, extremum seeking control and hybrid etc [15-50, 52, 53, 68-73]. Some techniques based on artificial neural networks, fuzzy logic, genetic algorithms are also presented in the literature.

Ali Reza Reisi et. al [23] 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.

Roberto Feranda et. al [24] presented a comparative study of ten most widely used maximum power point tracking algorithms using MATLAB/Simulink. Authors compared ten most common techniques namely constant voltage method, short circuit pulse method, open voltage method, perturb and observe method, temperature methods, incremental conductance method. According to the authors conclusion open voltage and short circuit pulse techniques provides low energy output in comparison with P & O and incremental conductance algorithms. Temperature methods continuously calculate and update the correct voltage reference. Authors analyzed the constant voltage technique is worst among the all ten MPPT methods.

Hairul Nissah Zainudin et. al [15] compared two MPPT techniques namely incremental conductance and P & O on the basis of simplicity, digital or analogical implementation, number of sensors required, 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. Authors analyzed the performance for three type of converters; Boost converter, buck converter and cuk converter. Paper concluded that the incremental conductance MPPT algorithm is best in all the cases.

Ragasudha C. P. et. al [38] presented design and implantation of standalone solar photovoltaic system for the purpose of battery charging with maximum power point tracking controller. Authors also developed a 600 W prototype for the same system for the performance analysis. They have chosen a buck converter to implement the incremental conductance MPPT techniques with IC MPT612. The designed system is effectively track the MPP of the PV panel and gives efficient operation.

M. Abdulkadir et. al [17] 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.

F. Z. Hamidon et. al [19] 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 analyzed the characteristics of the model on the basis of other parameters also like series resistance, shunt resistance and series parallel combination of PV modules.

Seok Il Go et. al [22] reviewed and implemented various available MPPT techniques in PSCAD/EMTDC with a user defined module of solar PV array. Authors compared the different techniques on the basis of their simplicity, merits and demerits in simulation studies in context with the grid connected photovoltaic systems. This paper is very beneficial in order to understand the existing MPPT control algorithms.

Ali Nasar Allah Ali et. al [21] discussed the 30 MPPT techniques. This work gives the complete understanding of maximum power point tracking algorithms available in literature. In this research work all the old and new MPPT methods observed and investigated thoroughly and some useful methods also introduced by the authors. New developed methods are; β method, system oscillation method, constant voltage tracker method, online MPP searches algorithm, variable inductor MPPT, POS control etc.

Mostafa Mosa et. al [18] 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 and obtain results are validated by using dSPACE 1103 control desk with a real time simulation.

C. P. Paul et. al [16] presented a new two stage DC-DC converter with a MPPT control algorithm for a solar photovoltaic system. Proposed maximum power point tracking utilizes the concept fuzzy logic control (FLC). Complete system with boost converter has been modeled and simulated by using Powersim software. Results are obtained under various atmospheric conditions and found that the system is more than 90% efficient with a fast tracking speed.

Ali F Murtaza et. al [20] identified problems related to P & O MPPT technique and presented a hybrid technique in MATLAB/Simulink. Presented hybrid technique combines the two most widely used general MPPT techniques i.e. P & O and fractional open circuit voltage technique. The proposed hybrid technique overcome the demerits of P & O algorithms and provides a fast tracking speed even under rapidly changing atmospheric conditions.

2.6INVERTER TOPOLOGIES FOR GRID CONNECTED PV SYSTEMS

Quan Li et. al [56] 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

Soeren Baekhoej Kjaer et.al [55] 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.

Different topologies are studied and compared on the basis of rating, cost of installation and maintenance required etc. Authors described centralized inverters as the past, string inverters and AC modules as present and multistring inverters, AC modules, AC cells as future in the field of solar photovoltaic systems.

Luigi G. Junior et.al [58] 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.

Frptz Schimpf et.al [57] 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.

2.7CONTROL STRATAGIES FOR GRID CONNECTED PHOTOVOLTAIC 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 [74-77, 79-85, 90-100].

Sachin Jain et. al [73] 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.

G. Shen et. al [84] introduced a new control scheme for the energy storage base solar photovoltaic grid connected systems. Developed control technique provides a novel interface between solar photovoltaic system and grid modeled as a virtual synchronous generator (VGS) and developed a control scheme for traditional synchronous generator.

A.Papavasiliou et.al [78] developed a current control scheme for grid connected PV generation system. The proposed technique combines the functions of deadbeat & PI controller, for a grid integrated three phase voltage source converter. Proposed system is resistant towards the grid disturbances, measurement errors, filter parameters etc. Simulation results prove the stability of proposed control technique. Developed controller has been analyzed in frequency domain and harmonic content of output current also found out.

D.Amorndechaphon et.al [79] proposed a new soft switching technique for single phase grid connected PV inverters. The proposed system consists of passive lossless snubber for boost converter and LLCC resonant inverter. Authors presented a simplified design procedure with suitable examples. Because of use of soft switching technique proposed boost converter works under low voltage and current stress, hence reduced overall switching losses. It can be observed from the results that proposed system efficiently applicable with small scale PV systems.

Linda Hassaine et.al [81] 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.

Yangheng yang et.al [80] presented the evaluation of behaviors of grid synchronization methods during the grid faults. Authors concluded that enhanced phase lock loop methods and second order generalized integrator based phase lock loop techniques are best techniques for the single phase PV systems as they provide fast adaptive filtering characteristics. This paper provides comparative study of some grid synchronization techniques in MATLAB using PLECC toolbox in case of grid faulty conditions.

Huijuan Li et.al [82] developed a control algorithm for three phase single stage grid connected PV systems with maximum power point tracking functionality as well as for real power injection and volt/var control.Automatic switching can be achieved in between MPPT mode and real power injection mode. To ensure the PV DC voltage stability authors has developed a method based on dynamic correction of inverter output.Performance analysis of proposed system has been carried out for fast solar irradiance changes and systems disturbances. Authors concluded that the proposed algorithm able to provide real and reactive power control and a well as ensure the PV DC voltage stability during changing system and atmospheric conditions.

Yu-Kang Lo et.al [76] 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.

Shuai Jiang et.al [83]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 [77] 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.

2.8FILTERS FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS

Filters are necessary to connect between converter and grid in order to eliminate the negative effects of power converters [78, 86-89]. Design of filters must be precise so that the whole system works under stable operation.

Jiri Lett et.al [89] presented a comparative study for different filter type for grid integration of renewable energy resources. Several filter types have been modeled and simulated in this paper. They are L filter, LC filter and LCL filter. However the functionality of the filter can be evaluated after the whole system is realized and filter will be connected between grid and output of the inverter.

Jeorge Dannehl et.al [88] presented a design procedure of LLC filter design for voltage source converter. Authors discussed the tuning procedure,performance, robustness and limitation of various solution presented in this paper with simulation and experimental results. Proposed active damping solution is attractive because of less complexity and less number of sensors required. For medium power distributed generation system low pass filter cab be a good choice but notch filters can be adapted for all cases.

2.9POWER 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 [101] 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 [102] 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.

2.10 CONCLUSION

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

CHAPTER 3

SOLAR PV TECHNOLOGY: AN OVERVIEW

3.1 INTRODUCTION

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

3.2 SOLAR PHOTOVOLTAIC 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:

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

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 photovoltaic system.Photovoltaic Cells are basically made up of a PN junction. When solar irradiancestrikes at the cell surface, the photons are absorbed by the atoms of semiconductor;and electrons get free from the negative layer. These free electrons findtheir way through an external circuit toward the positive layer making flow of electric current from the positive to the negative layer.

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 cellis 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 ofbeing grown into a single crystal, they are melted and poured into a mold. This mold makes asquare block which can be divided into square wafers resulting in less waste of space and material thanround single-crystal wafers.

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

Amorphous Silicon: This technology is newest in the area of thin film technology. In thistechnology amorphous silicon vapor is deposited on a couple of micro meter thickamorphous films on stainless steel rolls. Thistechnology utilizes only 1% of the material in comparisonwith crystalline silicon.

Table 3.1 Efficiency of different type of solar cells

	Cell	**Efficiency (%)**
1	Monocrystalline	12 – 18
2	Polycrystalline	12 – 18
3	Thin film	8 – 10
4	Amorphous Silicon	6 – 8

3.3 TYPES OF SPV SYSTEM DESIGN

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

1. Grid connected
2. Stand alone

Grid Connected: Grid connected systemsare mainly composed of a number of PV arrays, which convertthe 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.

Standalone System: 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 panelcan 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 operatingduring 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-fueled generators and provides cost effective solutionto remote areas. The main disadvantages are the cost and replacement of equipment and the loss of power during periods of poor solar irradiance.

3.4 CONCLUSION

Various design types of harnessing solar energy with the help of solar photovoltaic systems has been explained in this chapter.

CHAPTER 4

DESIGN, MODELING & SIMULATION OF STANDALONE SOLAR PHOTOVOLTAIC SYSTEM

4.1 INTRODUCTION

This chapterpresents the design and simulation of a standalone solar photovoltaic system. The main contents of this chapter are system description, different MPPT techniques used in this work and Simulink modelling, results and discussions.

4.2 SYSTEM DESCRIPTION

The proposed system mainly consists of PV array, DC-DC converter, battery bank along with MPPT controls. The block diagram of the proposed system is presented in Fig.4.1.

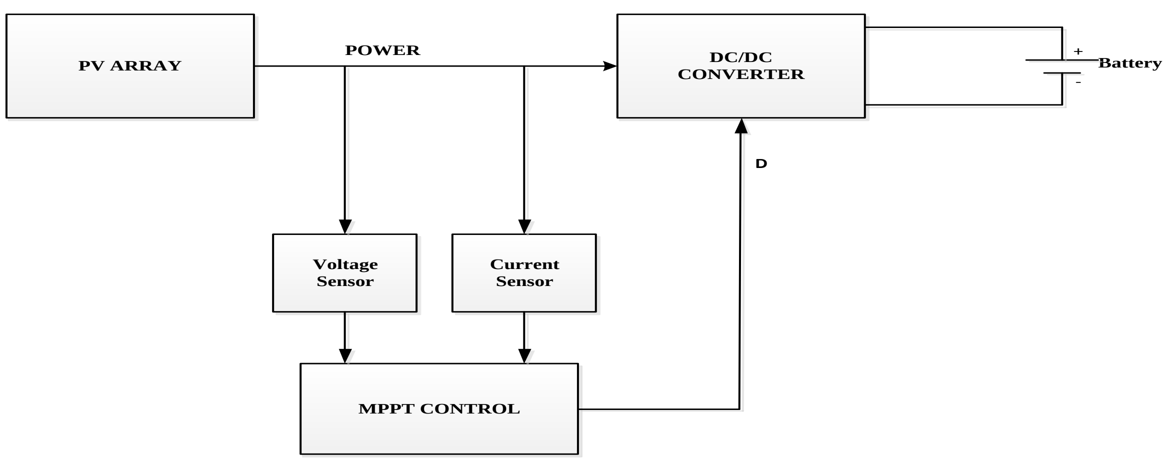


Fig. 4.1 Block diagram standalone of PV system

A DC-DC buck converter is used to step down the voltage level of PV array. Voltage and current sensors are used to sense the current and voltage of PV and different MPPT control includes P & O, incremental conductance and constant voltage are used in this work.

4.3 PV ARRAY MODELING

PV technology enables direct conversion of sunlight to electricity through semiconductor devices called solar cells. The power produced by solar cell is not enough for power generation applications. To obtain the higher power, solar cells are interconnected and hermetically sealed to constitute a photovoltaic module. Further, series – parallel combination of PV modules constitute a PV array. The equivalent circuit of PV module is presented in Fig. 4.2.

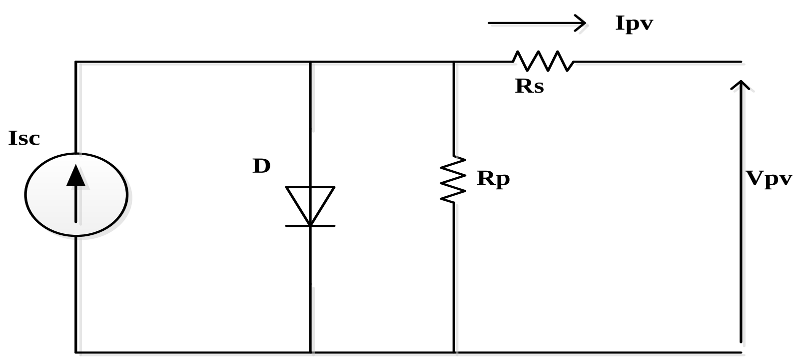


Fig. 4.2 Equivalent circuit model of solar module

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

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \quad (4.1)$$

Thus,

$$I_{PV} = I_{sc} - I_D - \frac{V_D}{R_p} \quad (4.2)$$

The reverse saturation current I_{rs} is given as

$$I_{rs} = I_{scref} + [\exp\left(\frac{qVoc}{NskAT}\right) - 1] \quad (4.3)$$

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

$$I_o = I_{rs}\left[\frac{\left(\frac{T}{T_{ref}}\right)^3 e^{qCg}}{Ak} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (4.4)$$

The basic equation that describes the current output of the PV module of the single-diode model is given in equation (4.5).

$$I_{PV} = I_{sc}N_p - N_sI_o\left[\exp\left\{\frac{q(V_{PV}+I_{PV}Rs)}{N_sAkT}\right\} - 1\right]V_{PV} + \frac{I_{PV}Rs}{Rp} \quad (4.5)$$

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 = 72. N_p is the number of cells connected in parallel = 1.

4.4DC - DC BUCK CONVERTER

DC – DC 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, flyback, buck-boost etc. The choice of topology depends on system requirements and its applications. In this paper, DC-DC buck converter is designed to step down the PV voltage. The circuit diagram for buck converter is presented in Fig. 4.3, and the data of various parameters of buck converter are presented in Table 4.1.

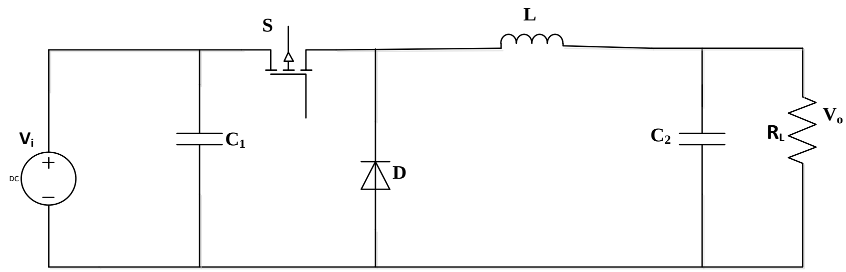


Fig. 4.3DC - DC buck converter

Table 4.1Various parameters of buck converter

S. No.	Parameter	Formula
1.	Input Capacitance (C_1)	$\frac{I_{PV}(1-\mathrm{D})}{2\Delta V_{PV} f_{sw}}$
2.	Inductance (L)	$\frac{V_{PV}(1-\mathrm{D})}{2\Delta i_L f_{sw}}$
3.	Output Capacitance (C_2)	$\frac{\Delta i_L}{8\Delta V \ \ f_{sw}}$

4.5BATTERY STORAGE SYSTEM

The power generated from PV system is fluctuating in nature, therefore there is a need of storage systems. In addition, energy storage systems are useful in both utility and small scale applications. The battery storage systems in grid connected systems helps to achieve the objectives like mitigation of the variability and intermittency of PV power by ensuring the maintenance of constant voltage and frequency meeting the peak electricity demand during low power generation from PV system. There are many battery models are available in literature. However, this paper uses the lead acid battery. This model is chosen for its simplicity, low cost and easy availability.

4.6MAXIMUM POWER POINT TRACKING TECHNIQUES

Maximum power point tracking is necessary in order to track the maximum power point (MPP) under varying meteorological parameters. 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. In this paper some most widely used MPPT algorithms including perturb and observe, incremental conductance and constant voltage have been used.

4.6.1 Perturb and Observe (P & O) technique

Perturb and observe method is simple method which can be implemented by applying perturbation to the reference voltage or reference current signal of the solar PV system. 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. This method is also known as 'hill climbing method'. A flowchart illustrating this method is shown in Fig. 4.4.

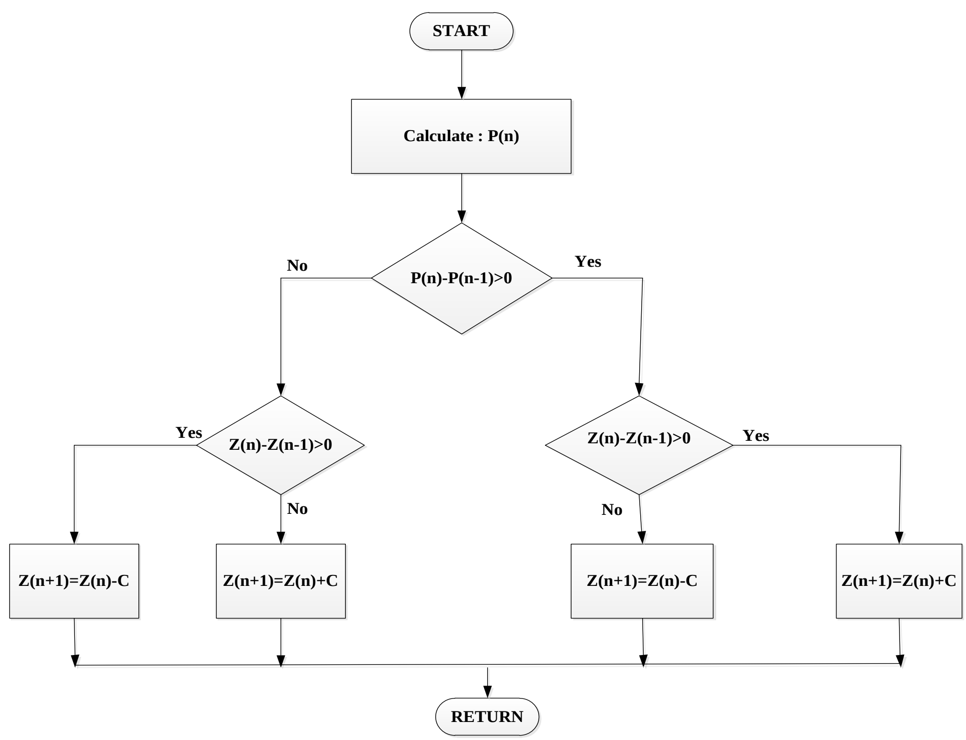


Fig. 4.4 Flowchart for Perturb & Observe MPPT technique

4.6.2 Incremental conductance method

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.

$$\frac{dP}{dV} = I + v\frac{dI}{dV} = 0 \quad (4.6)$$

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

$$\frac{dI}{dV} \cong \frac{\Delta I}{\Delta V} = -\frac{I_{MPP}}{V_{MPP}} \quad (4.7)$$

$$\frac{dP}{dV} = 0 \qquad \frac{\Delta I}{\Delta V} = -\frac{I}{V} \qquad \text{at MPP (4.8)}$$

$$\frac{dP}{dV} > 0 \qquad \frac{\Delta I}{\Delta V} > -\frac{I}{V} \qquad \text{left side of MPP (4.9)}$$

$$\frac{dP}{dV} < 0 \qquad \frac{\Delta I}{\Delta V} < -\frac{I}{V} \qquad \text{right side of MPP (4.10)}$$

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 Fig. 4.5.

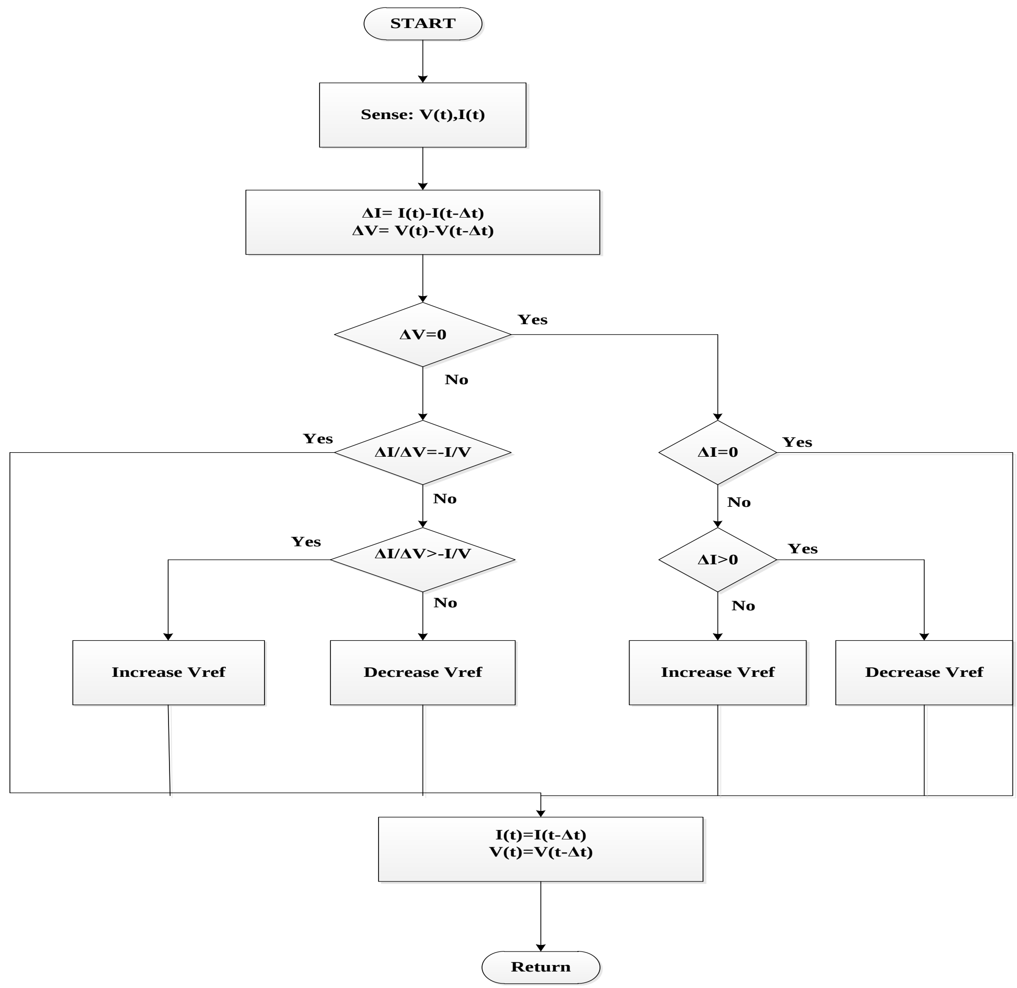


Fig. 4.5 Flowchart for Incremental Conductance MPPT technique

4.6.3 Constant voltage technique

In this method, operating point of PV module is kept near the maximum power point by regulating the module/array voltage. It should be matched with the fixed reference voltage equal to the V_{MPP} of PV system. The constant voltage algorithm is the simplest MPPT control technique.

4.7 MATLAB/SIMULINK MODELING OF SYSTEM

In this paper a 2 kW PV array with battery storage is used for simulations. To extract maximum power from PV array three MPPT algorithms namely P & O, incremental conductance and constant voltage have been used. The system was simulated in MATLAB/Simulink environment. A MATLAB/Simulink model of solar PV module is shown in Fig. 4.6. In addition, PV system consisting of PV array, DC-DC converter, charge controller and MPPT control is also presented in Fig. 4.7.

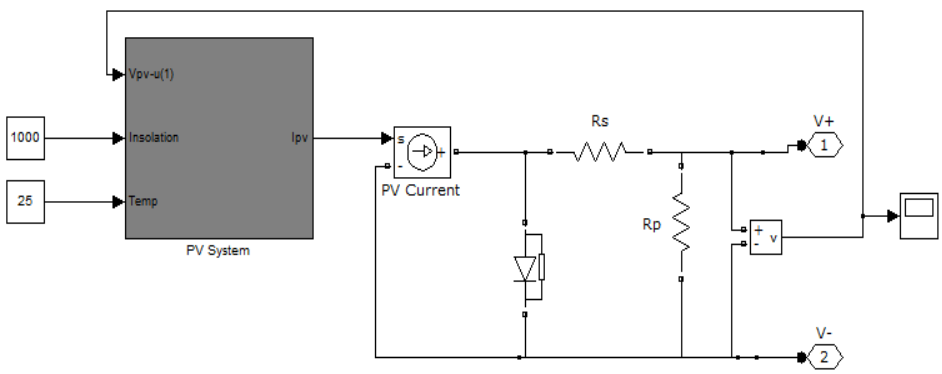


Fig. 4.6 MATLAB/Simulink model for solar PV system

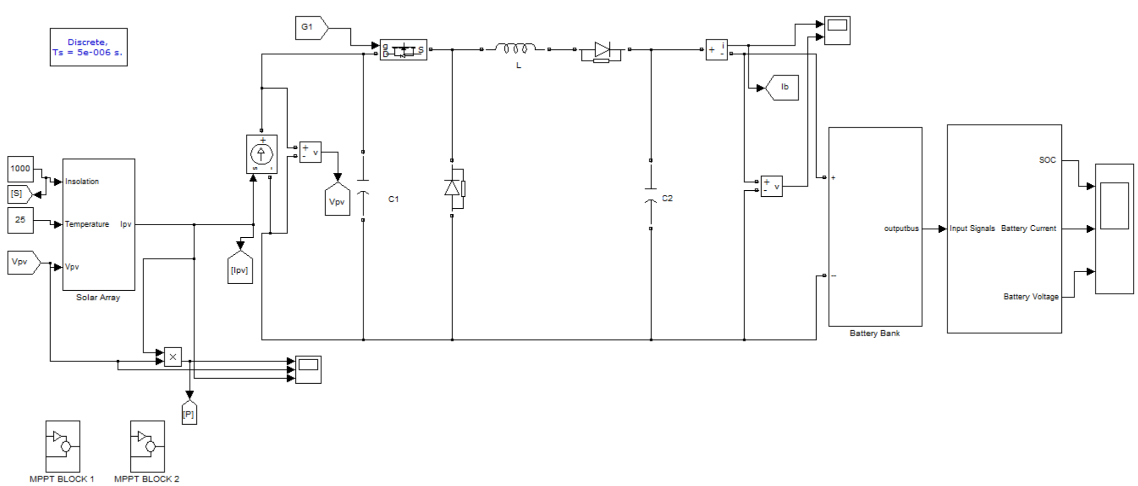


Fig. 4.7 MATLAB/Simulink model for 2kW PV array with MPPT for battery charging

4.8 SIMULATION RESULTS

Three MPPT techniques are implemented in MATLAB/Simulink environment to study and compare the dynamic performance of PV system. All simulations are performed under different meteorological conditions. These conditions include constant solar irradiance and temperature, varying irradiance and constant temperature, constant irradiance and varying temperature and varying irradiance and temperature.

4.8.1 Performance analysis of PV system at constant solar irradiance and temperature

The graphical representation of P & O technique, incremental conductance technique and constant voltage MPPT technique are shown in Fig 4.8 –Fig 4.9, Fig 4.10 – Fig 4.11 and Fig 4.12 – Fig 4.13 respectively. Also, the analytical performance of three MPPT techniques is presented in Table 4.2.

From Fig 4.8 – Fig 4.13, it is observed that the power ripple and voltage fluctuations are highest in case of P & O and least in constant voltage where as response time and battery charging voltage is almost same in all the three MPPT techniques. The oscillations in P & O is not constant and oscillating between 0 -59 A. It is concluded that the overall performance of constant voltage technique is better as compared to other techniques.

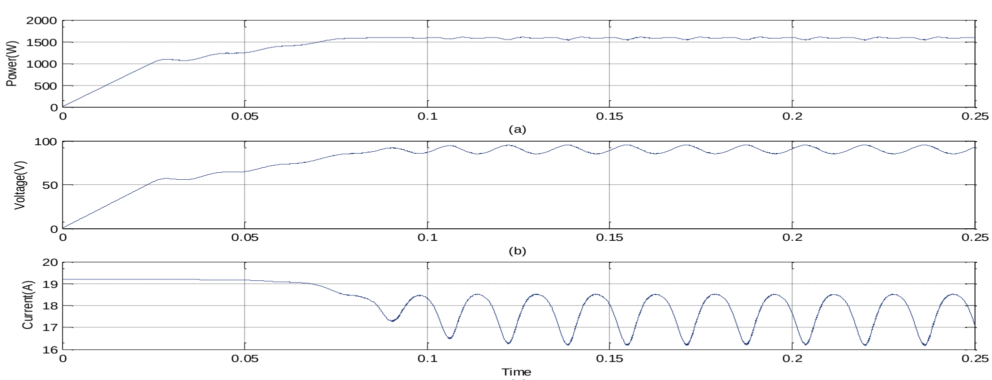


Fig. 4.8 Performance of PV array (a) Power (b) Voltage (c) Current at constant e and temperature using P & O MPPT technique

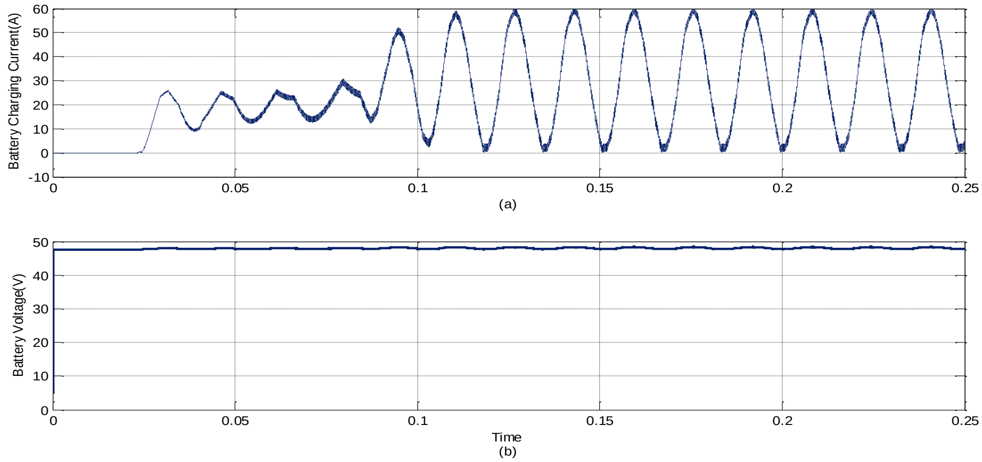


Fig. 4.9 Performance of PV array (a) battery charging current (b) battery charging voltage at constant irradiance and temperature using P & O MPPT technique

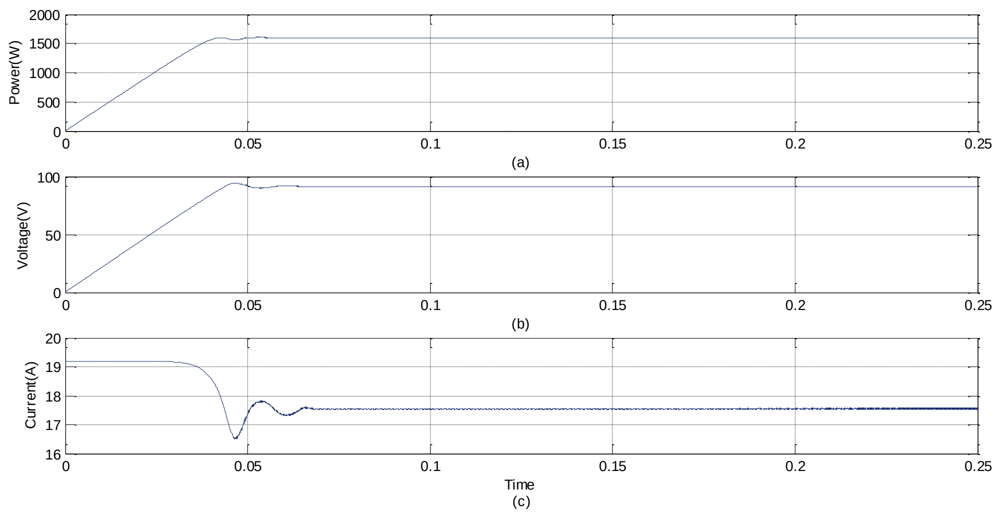


Fig. 4.10 Performance of PV array (a) Power (b) Voltage (c) Current at constant irradiance and temperature using incremental conductance MPPT technique

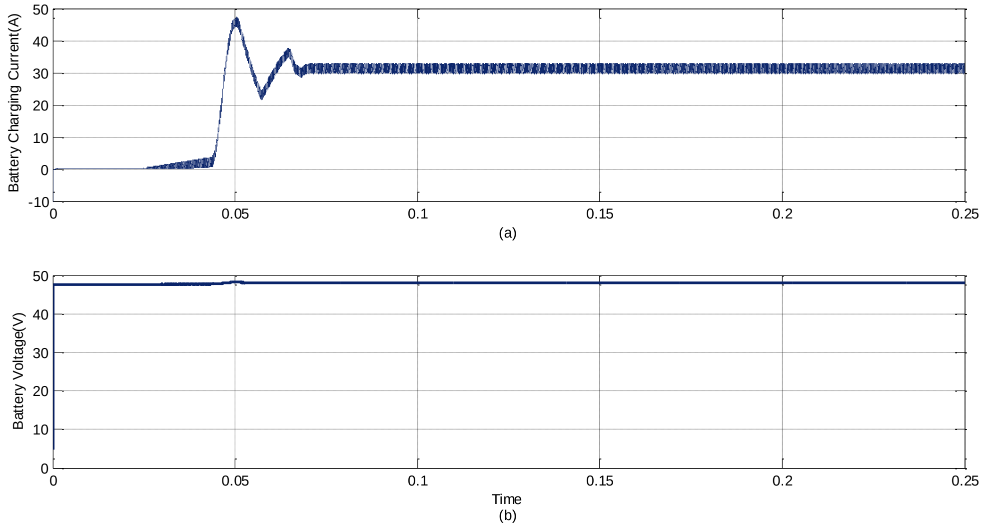


Fig. 4.11 Performance of PV array (a) battery charging current (b) battery charging voltage at constant irradiance and temperature using incremental conductance MPPT technique

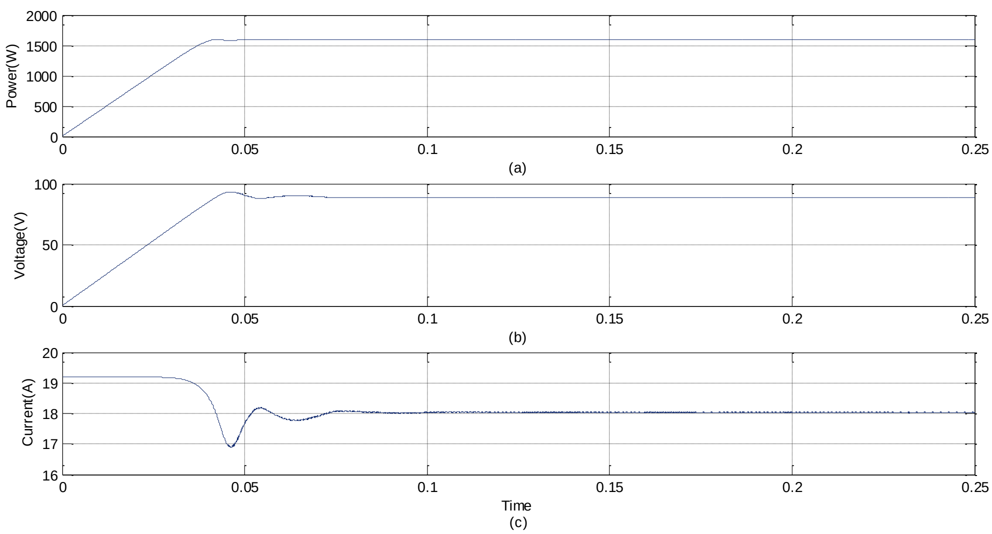


Fig. 4.12 Performance of PV array (a) Power (b) Voltage (c) Current at constant irradiance and temperature using constant voltage MPPT technique

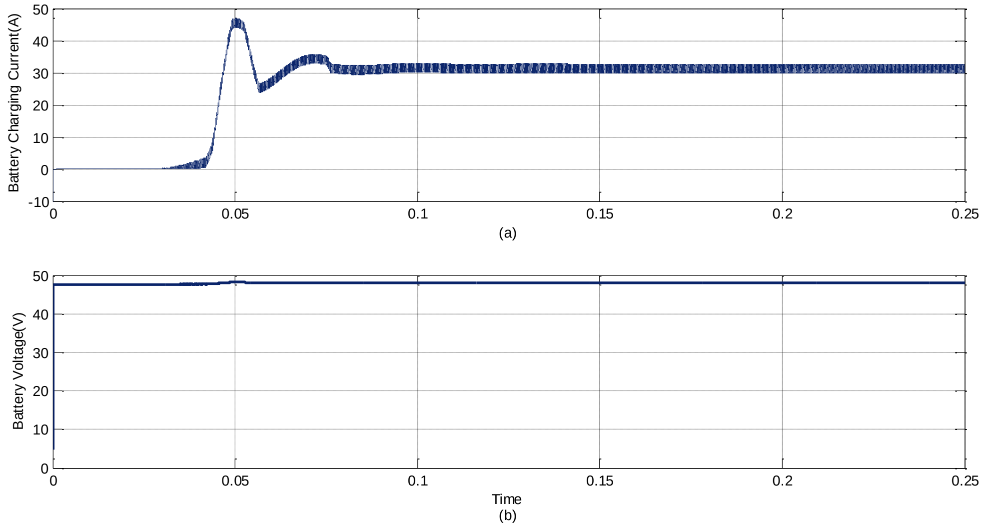


Fig. 4.13 Performance of PV array (a) battery charging current (b) battery charging voltage at constant irradiance and temperature using constant voltage MPPT technique

Table 4.2 Performance of P & O, Incremental Conductance and Constant Voltage MPPT techniques

Parameters	MPPT Techniques		
	P & O	Incremental Conductance	Constant Voltage
Power ripple (W)	65	0.7	0.3
Voltage fluctuations (V)	4.1	1.47	1.35
Response time (s)	0.0894	0.07	0.081
Battery charging voltage (V)	47.51	47.79	48
Battery charging current (A)	Not constant oscillating between 0 to 59 A throughout the period	31.6	32.7

It is mentioned above that the 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. To incorporate such practical conditions, performance analysis of PV system at varying irradiance and constant temperature, constant irradiance and varying temperature and varying irradiance and temerature is carried out. The effect of solar irradiance and temperature on PV output is presented in Fig. 4.14 and Fig. 4.15 respectively. It is clearly mentioned from Fig. 4.14 and Fig. 4.15 that there is a large impact of these parameters on PV output.

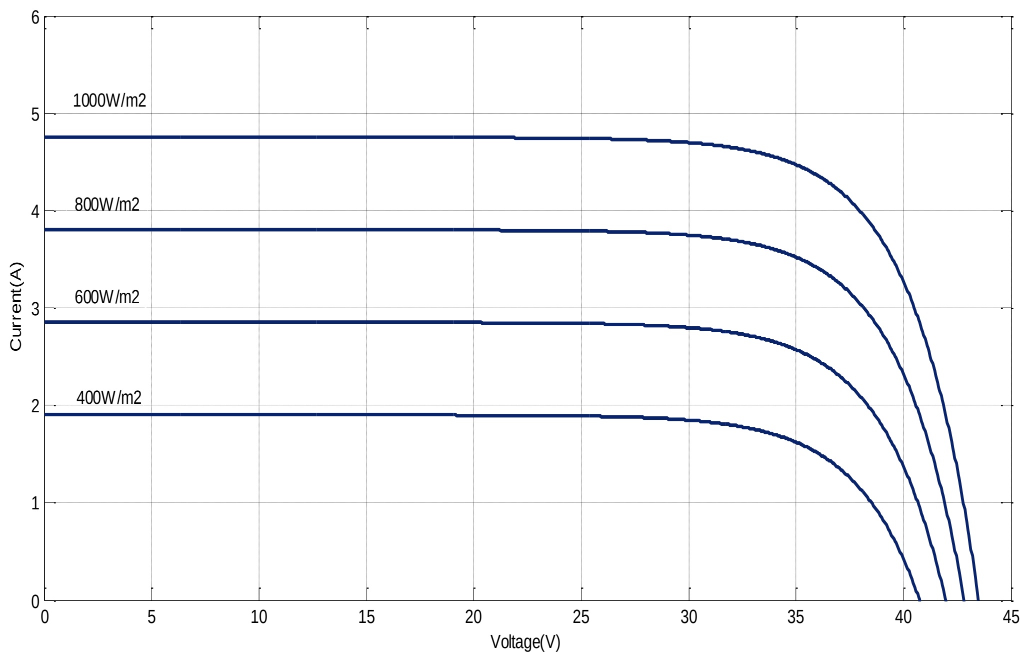


Fig. 4.14 Performance of PV system with varying irradiance

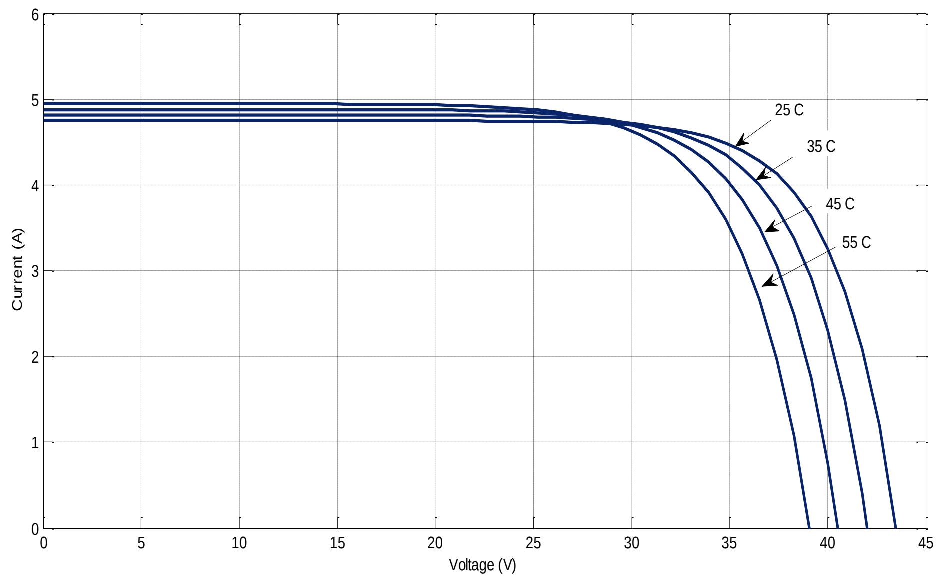


Fig. 4.15 Performance of PV system with varying temperature

Further, it is observed that the PV output current varies with irradiance. The operating point changes with the solar irradiance, temperature and load conditions. With the increase in operating temperature the output current increases but the value of voltage decreases drastically. This results in the reduction of the output power.

4.8.2 Performance analysis of PV system at varying irradiance and constant temperature

The performance of PV systems using P & O, incremental conductance and constant voltage is presented in Fig. 4.16 , Fig 4.18, Fig 4.20 for changing irradiance and constant temperature respectively. Further the battery charging characteristics are presented in Fig 4.17, Fig 4.19, Fig 4.21using P & O, incremental conductance and constant voltage approach.

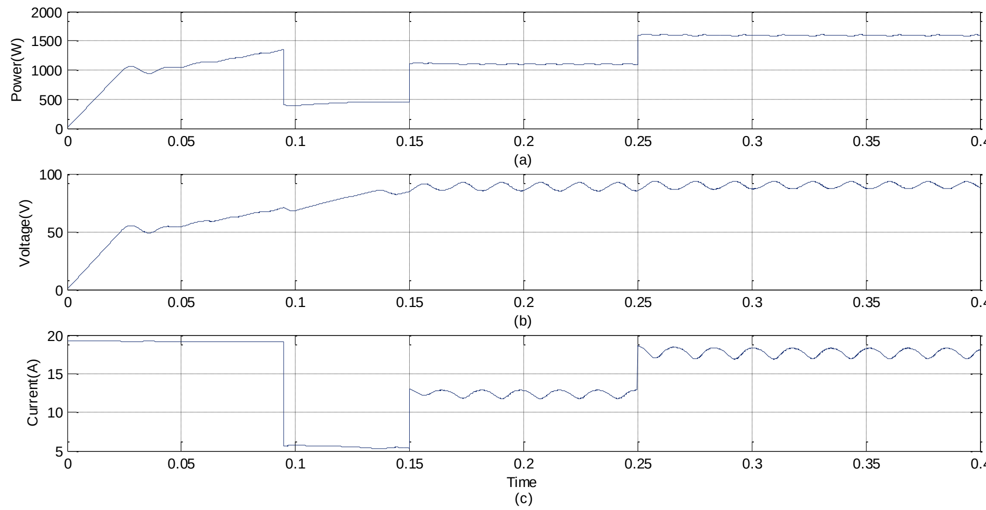


Fig 4.16 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and constant temperature using P & O MPPT technique

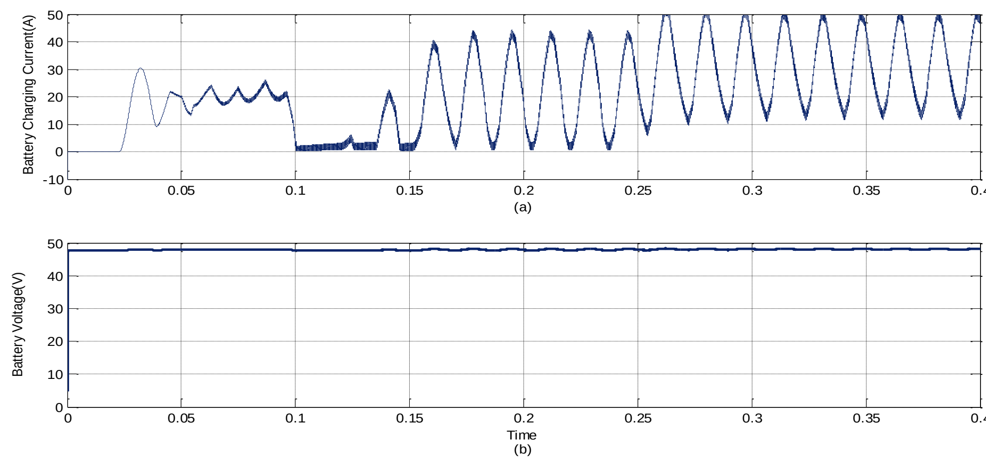


Fig. 4.17 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and constant temperature using P & O MPPT technique

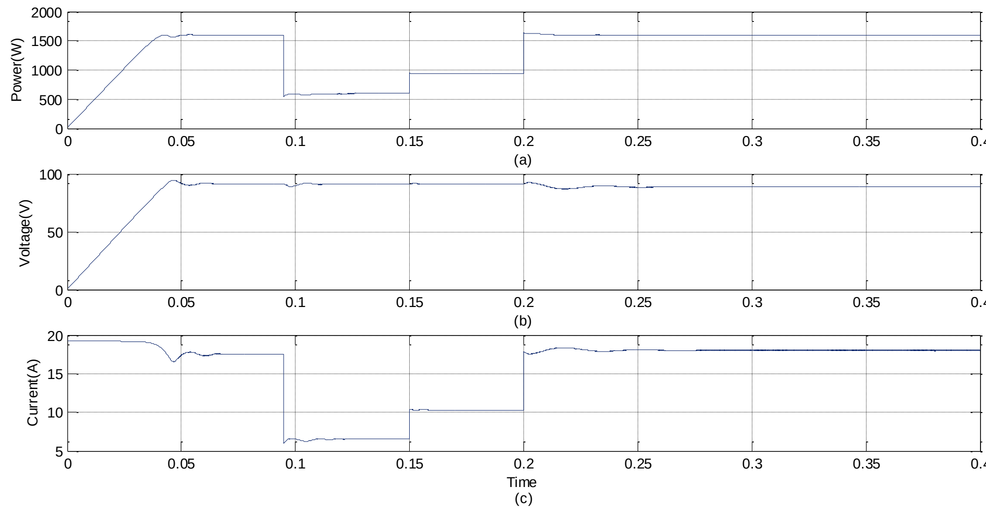


Fig. 4.18 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and constant temperature using incremental conductance MPPT technique

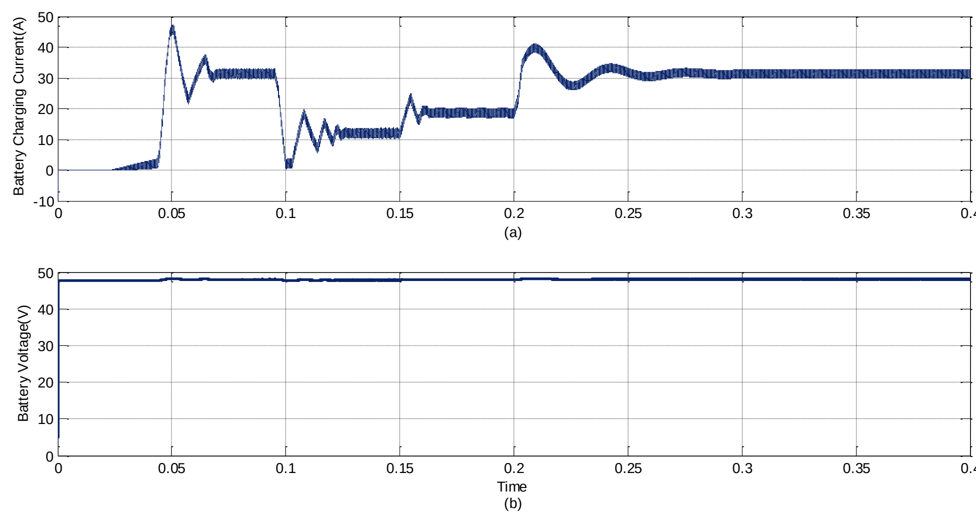


Fig. 4.19 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and constant temperature using incremental conductance MPPT technique

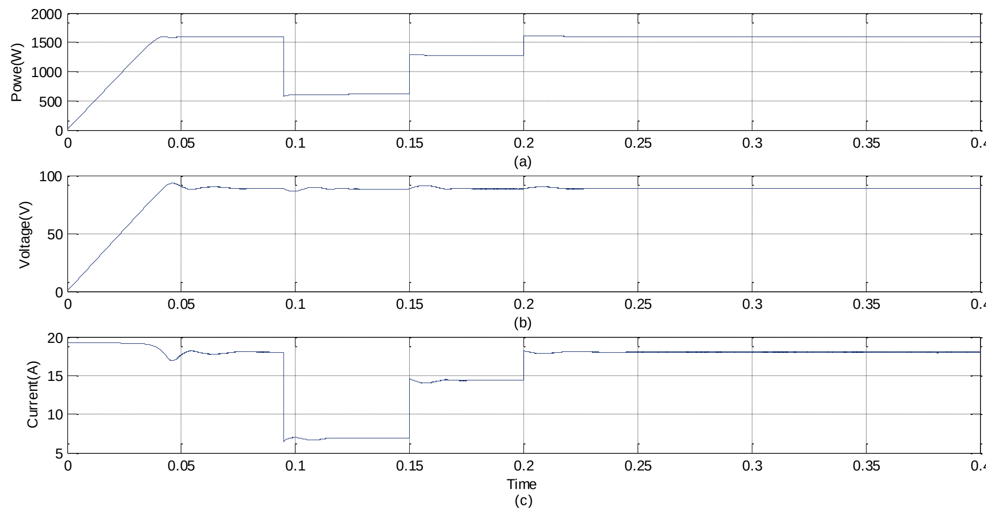


Fig. 4.20 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and constant temperature using constant voltage MPPT technique

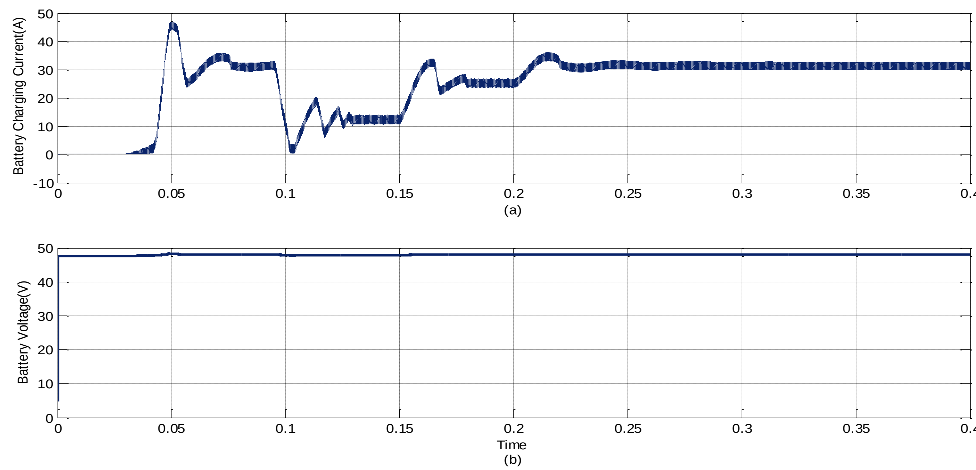


Fig. 4.21 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and constant temperature using constant voltage MPPT technique

Performance analysis of these MPPT techniques is carried out at fixed value of temperature of 25˚C and varying solar irradiance. The solar irradiance is suddenly varied at 300 W/m^2, 700 W/m^2 from STC i.e. 1000 W/m^2. In this case, it is observed that the energy extracted from PV system is less as compared to the constant solar irradiance and temperature. From Table 4.3, it is depicted that the performance of constant voltage is better as compared to other technique in terms of power ripple, voltage fluctuations, response time and battery charging time. However, this technique is not suitable suddenly changing metrological parameters like solar irradiance and temperature. Therefore, incremental conductance technique is better as compared to other techniques as mentioned above under dynamical conditions.

Table 4.3 Performance of P & O, incremental conductance and constant voltage MPPT techniques

Parameters	MPPT Techniques		
	P & O	Incremental Conductance	Constant Voltage
Power ripple (W)	25	0.8	1.1
Voltage fluctuations (V)	4.7	2.7	1.6
Response time (s)	0.26	0.27	0.23
Battery charging voltage (V)	47.64	47.78	47.9
Battery charging current (A)	Not constant oscillating between 10 to 50 A throughout the period	32	31

4.8.3 Performance analysis for constant solar irradiance and varying temperature

It is also observed that there is direct impact of solar cell temperature on output of solar cell and there is decrease in voltage about 0.023 V per degree rise in temperature. Therefore, the study of impact of temperature in PV system is utmost important. The performance of PV system at solar irradiance of 1000 W/m^2 and different values of temperature i.e. 20˚C, 37˚C and 50˚C is carried out to understand the impact of cell temperature of PV output and presented in Fig 4.22 – Fig 4.27 for three MPPT techniques.The analytical results are also presented in Table 4.4. From this analysis, it is observed that the performance of constant voltage is better as compared to the P & O and incremental conductance methods. As mentioned above constant voltage approach cannot be employed for practical cases, hence incremental conductance technique is best suitable for this case.

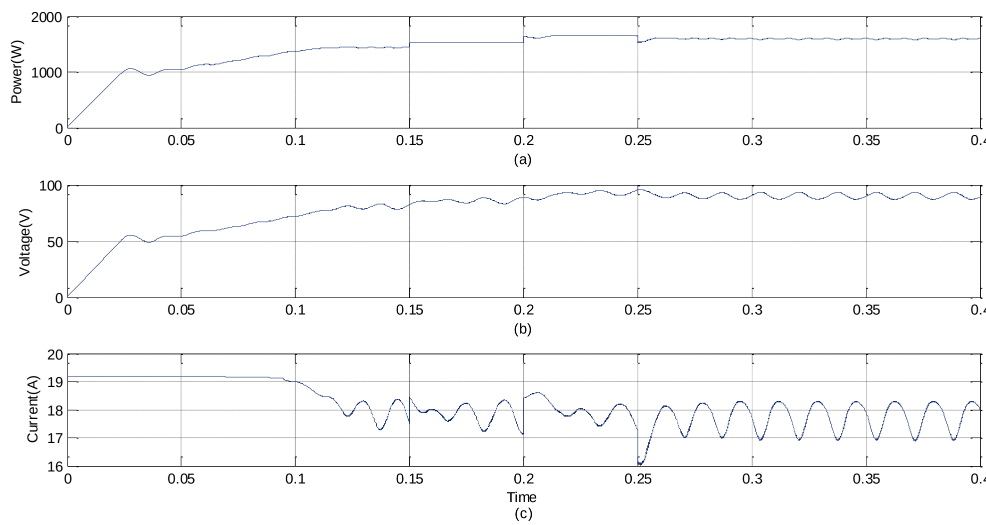


Fig. 4.22 Performance of PV array (a) Power (b) Voltage (c) Current at constant irradiance and varying temperature using P & O MPPT technique

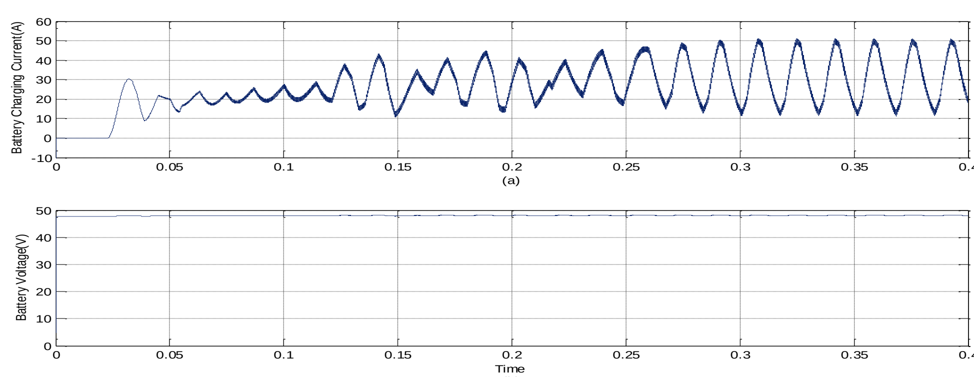


Fig. 4.23 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and constant temperature using P & O MPPT technique

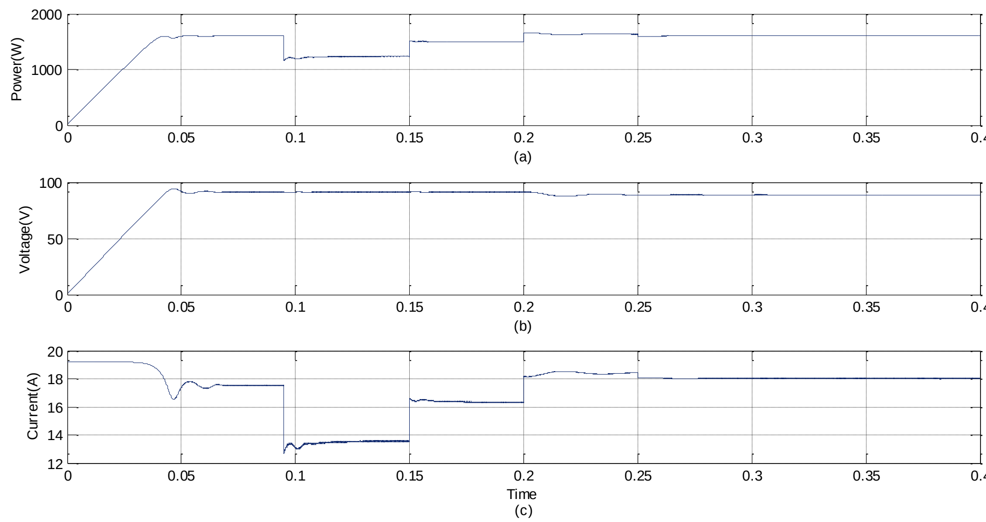


Fig. 4.24 Performance of PV array (a) Power (b) Voltage (c) Current at constant irradiance and varying temperature using incremental conductance MPPT technique

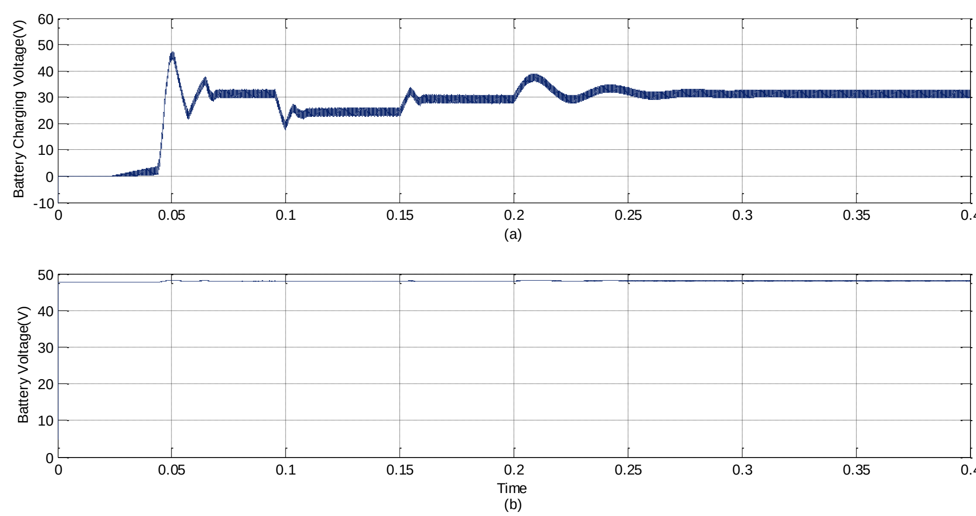


Fig. 4.25 Performance of PV array (a) battery charging current (b) battery charging voltage at constant irradiance and varying temperature using incremental conductance MPPT technique

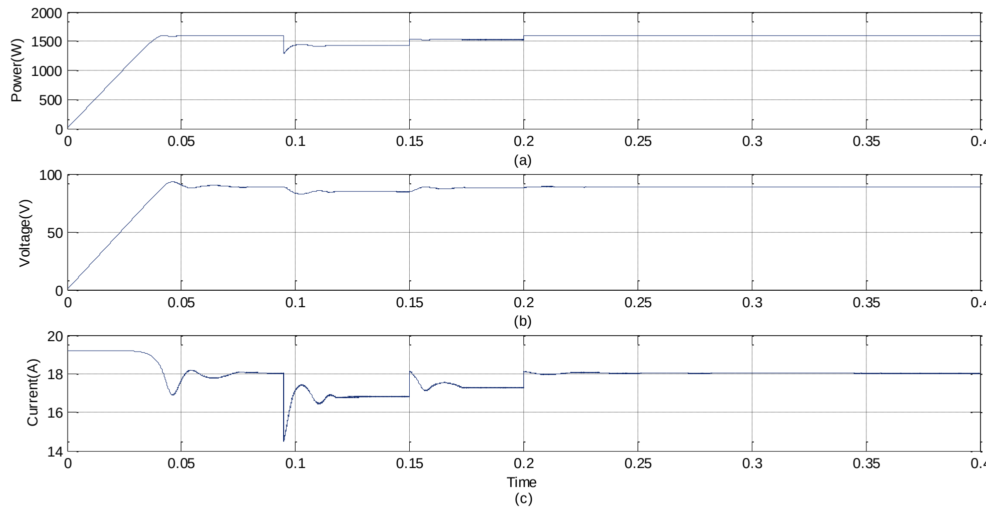


Fig. 4.26 Performance of PV array (a) Power (b) Voltage (c) Current at constant irradiance and varying temperature using constant voltage MPPT technique

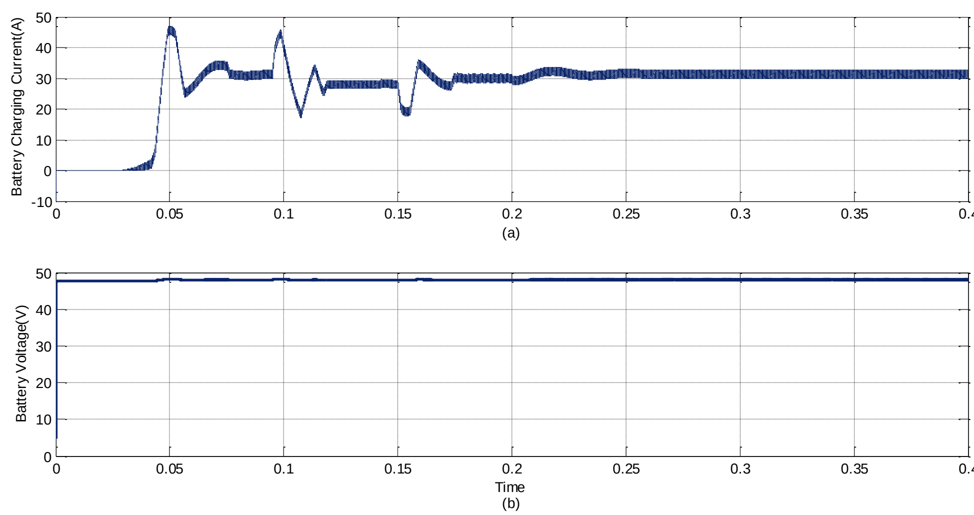


Fig. 4.27 Performance of PV array (a) battery charging current (b) battery charging at constant irradiance and varying temperature using constant voltage MPPT technique

Table 4.4 Performance of P & O, incremental conductance and constant voltage MPPT techniques

Parameters	MPPT Techniques		
	P & O	Incremental Conductance	Constant Voltage
Power ripple (W)	20	4	1.7
Voltage fluctuations (V)	3.5	2.9	1.5
Response time (s)	0.28	0.28	0.24
Battery charging voltage (V)	47.68	47.75	47.89
Battery charging current (A)	Not constant oscillating between 0 to 59 A throughout the period	31.96	31.89

4.8.4 Performance analysis for varying solar irradiance and temperature

It is clearly observed that there is a significant impact of solar irradiance and temperature on the PV power generation. Therefore it is utmost important to study the impact of these parameters simultaneously. Keeping in view, performance analysis of various MPPT techniques under varying irradiance and temperature is carried out and presented in Fig. 4.28, Fig. 4.29, Fig. 4.30, Fig. 4.31, Fig. 4.32, and Fig. 4.33 using P & O, incremental conductance and constant voltage MPPT techniques respectively.

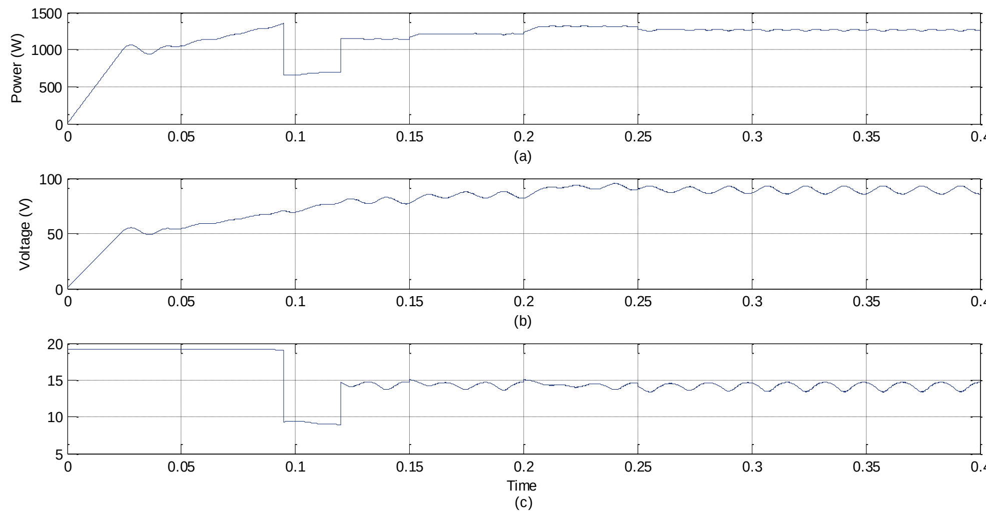


Fig. 4.28 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and temperature using P & O MPPT technique

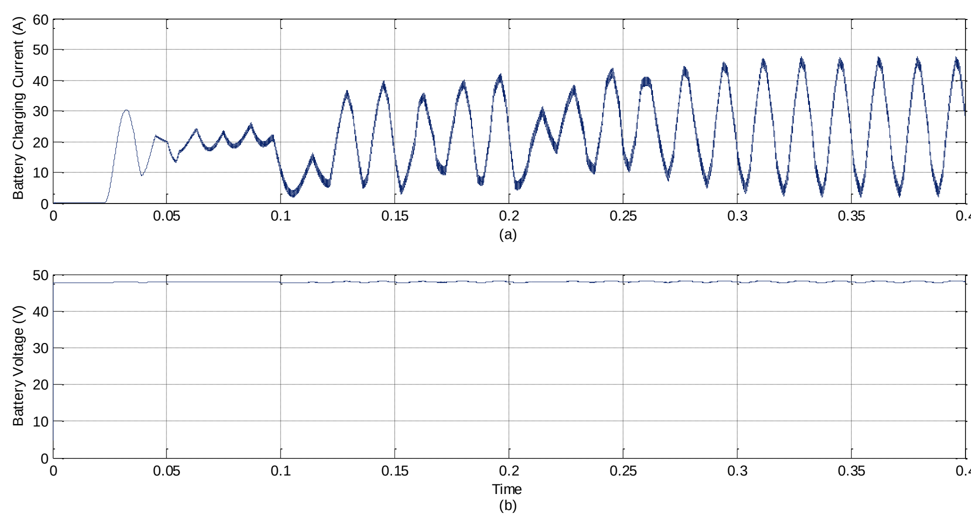


Fig. 4.29 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and temperature using P & O MPPT technique

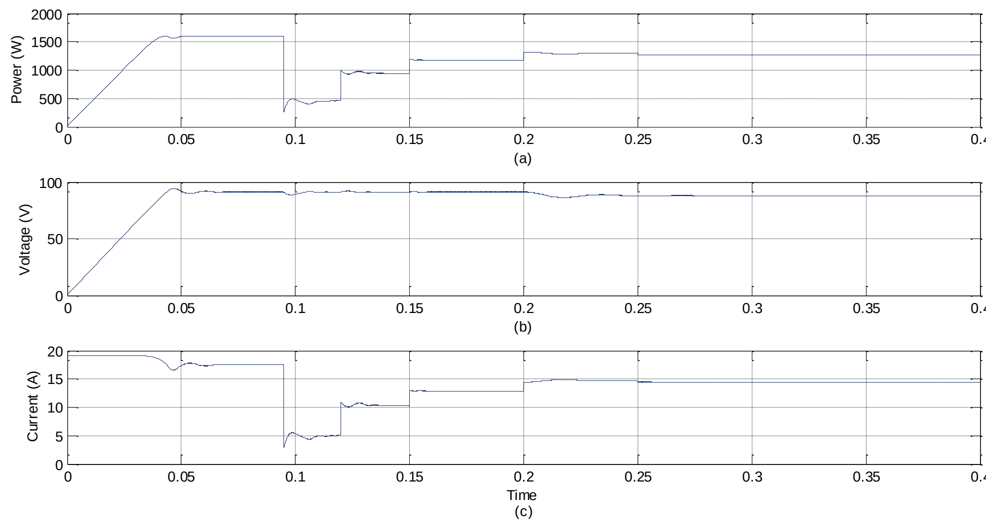


Fig. 4.30 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and temperature using incremental conductance MPPT technique

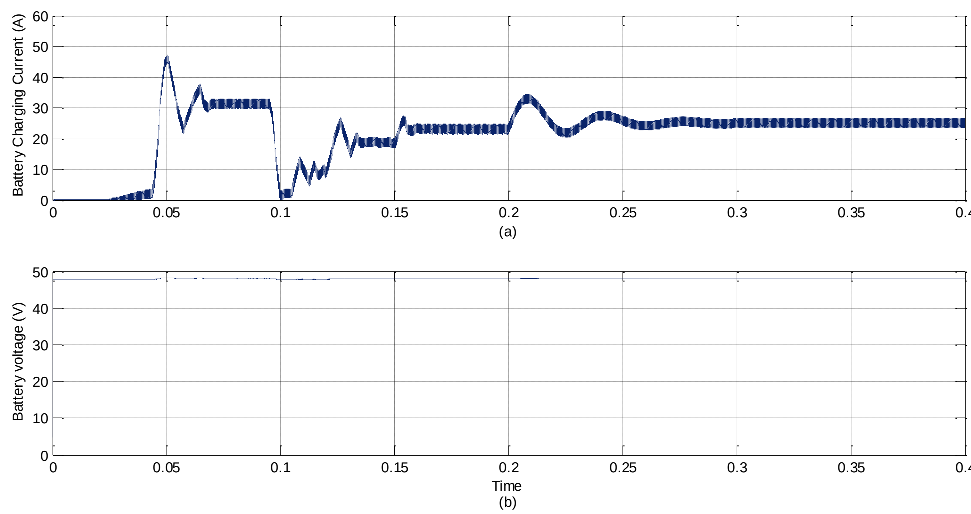


Fig. 4.31 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and temperature using incremental conductance MPPT technique

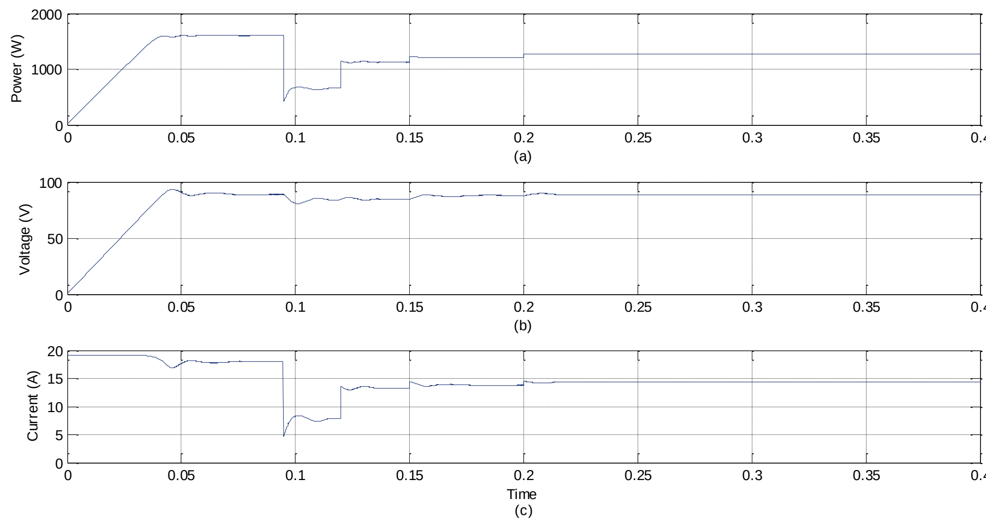


Fig. 4.32 Performance of PV array (a) Power (b) Voltage (c) Current at varying irradiance and temperature using Constant Voltage MPPT technique

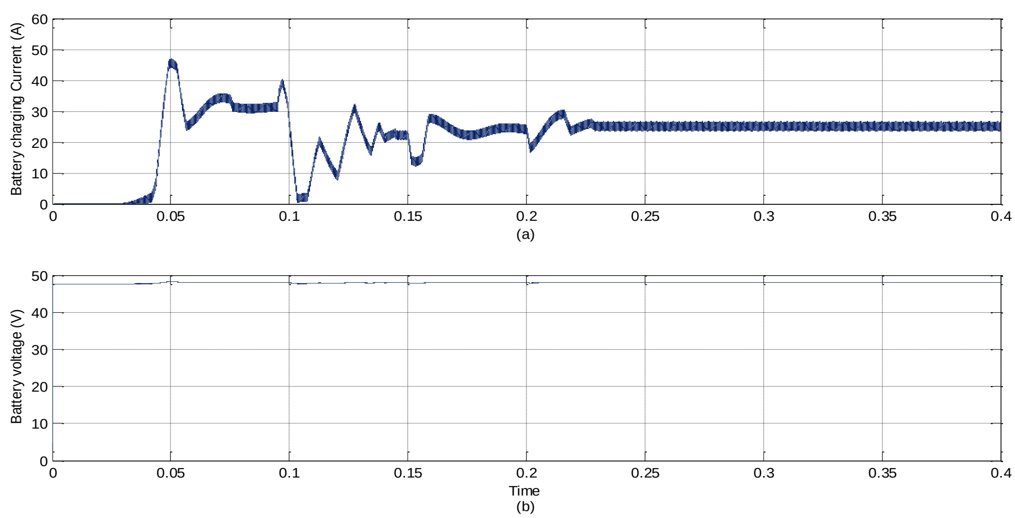


Fig. 4.33 Performance of PV array (a) battery charging current (b) battery charging voltage at varying irradiance and temperature using Constant Voltage MPPT technique

Table 4.5 Performance of P & O, incremental conductance and constant voltage MPPT techniques

Parameters	MPPT Techniques		
	P & O	Incremental Conductance	Constant Voltage
Power ripple (W)	22	3.5	1.5
Voltage fluctuations (V)	3.2	1.8	1.3
Response time (s)	0.24	0.28	0.22
Battery charging voltage (V)	47.89	47.94	48.1
Battery charging current (A)	Not constant oscillating between 0 to 45 A throughout the period	26.97	28.1

In this case performance analysis is carried out for varying irradiance ant temperature. P &O MPPT technique contains more oscillations then in varying temperature and constant irradiance conditions and battery charging current is also oscillatory. Incremental conductance technique performs pretty well in this situation but it has large response time. Constant voltage MPPT technique again gives higher amount of extracted energy than other two techniques.

4.9 CONCLUSION

In this chapter, performance analysis of three MPPT techniques namely P & O, Incremental Conductance and Constant Voltage is carried out and presented with standalone solar photovoltaic system.

CHAPTER 5

DESIGN, MODELING & SIMULATION OF SINGLE PHASE GRID CONNECTED SOLAR PHOTOVOLTAIC SYSTEM

5.1 INTRODUCTION

Grid connected photovoltaic systems are gaining more and more attention during the past decade because it has the advantage of more effective utilization of generated power. However, there are number of technical requirements which need to be satisfied from both sides. Some conditions which must be satisfied are:

1. Frequency of PV plant should be same as utility
2. Voltage level should be same for both sides
3. For synchronization it is utmost important that the phase sequence of PV system should be same with utility grid.

This chapter consisting of detailed modeling of single phase grid connected PV system with design detail of each component. Basically two PV arrays with different power ratings have been connected with the single phase utility grid. Modeling of the system and its component is explained in this chapter followed by the simulation results.

5.2 SYSTEM DESCRIPTION

The proposed system mainly consists of PV array, DC-DC converter with MPPT control and a single phase H-bridge inverter along with control algorithm. The block diagram of the proposed system is presented in Fig.5.1. A DC-DC boost converter is used to step up the voltage level of PV array. MPPT control includes P & O and a modified P & O algorithm which are used to track the MPP of solar PV system.

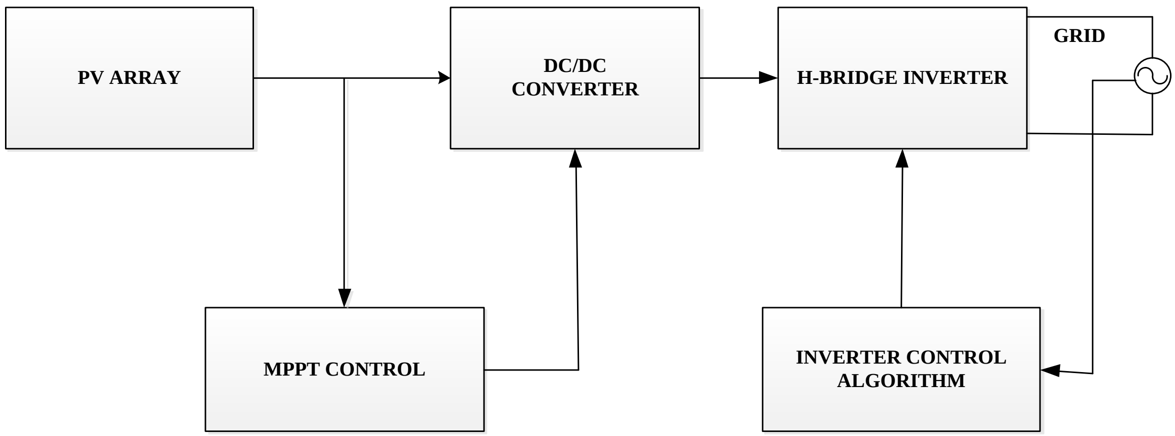


Fig. 5.1 Single phase grid connected PV system

5.3 COMPONENT MODELING

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

5.3.1Modeling of PV array

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.

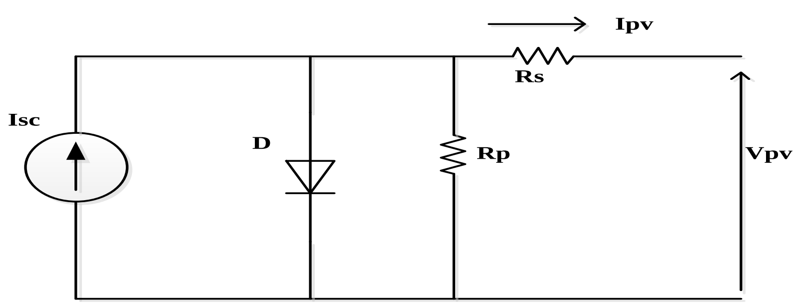


Fig. 5.2 Equivalent circuit model of solar module

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

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \quad (5.1)$$

Thus,

$$I_{PV} = I_{sc} - I_D - \frac{V_D}{R_p} \quad (5.2)$$

The reverse saturation current I_{rs} is given as

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

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 (1.38×10^{-23} J K^{-1}), q is the electronic charge (1.602×10^{-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 datasheet of 250 W_p solar PV module is presented in Table 5.1.

Table 5.1 Datasheet for 250 W_p single PV module

Parameter	**Variable**	**Value**
Maximum power	Pm	250 W
Voltage at maximum power	Vm	31.3 V
Current at maximum power	Im	8.15 A
Open circuit voltage	Voc	37.08 V
Short circuit current	Isc	8.56 A
Total No. of cells in Series	Ns	36
Total No. of cells in Parallel	Np	1
Temp. Coefficient of Isc	Ki	(0.065+0.015)%/C
Temp. Coefficient of Voc	Kv	-(160+-20)mV/C

5.3.2Modeling of DC/DC boost converter

The input for the DC converter is from the solar panel which had highly non linear output characteristics. The duty ratio of the DC converter is based on the Maximum power point of solar cell. The various types of DC/DC converters were analyzed in the second chapter on literature review. Even though the fly back converter suits the most for this kind of application, the transformer design is very complex and finding a suitable vendor for manufacturing is difficult. The full bridge is highly effective for high power applications but not for these low power ratings. Hence it was decided to choose the half bridge Isolated DC/DC converter for this project.

A general half bridge DC/DC boost converter is modified by decomposing the DC bus capacitor into two capacitors. A high frequency transformer is implemented in the boost converter circuit in order to step up the low voltage into a value DC voltage. Further a half bridge diode rectifier has been used to convert the output of HFT in DC again.

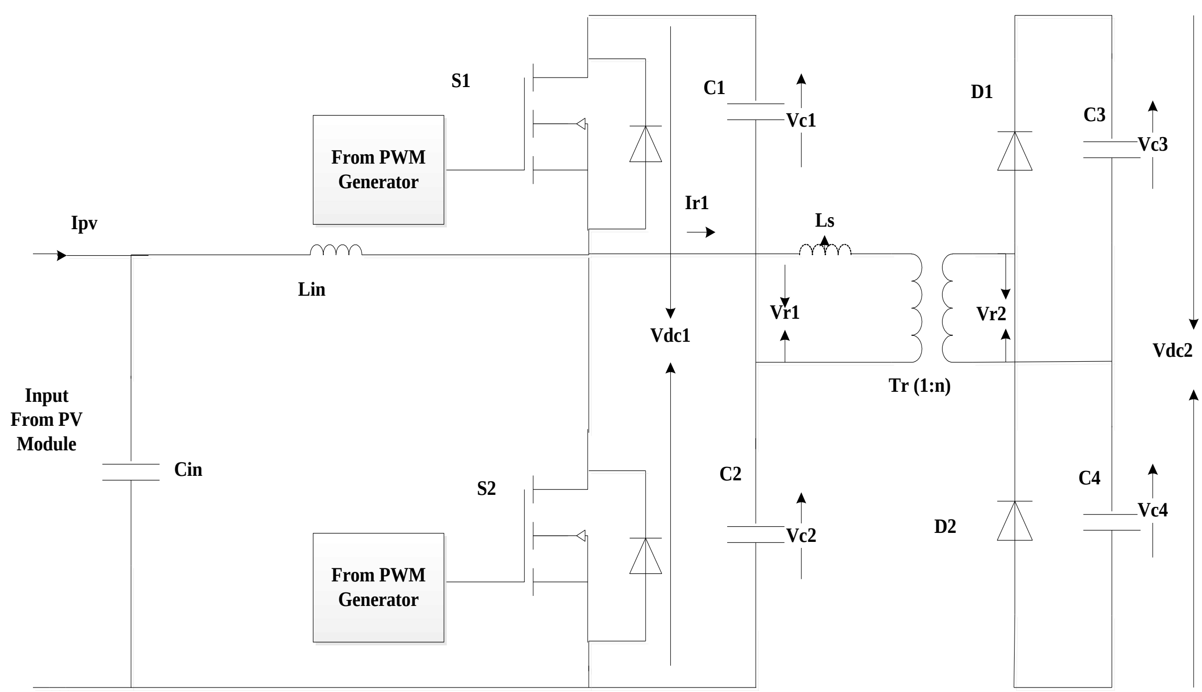


Fig. 5.3 Half bridge DC/DC boost converter with HFT

Table 5.2 Parameter calculations for DC/DC boost converter

Parameter	Formula	Value
PV Input voltage (V_{PV})		30-37 V
Switching Frequency (f_{sw})		21kHz
Duty Cycle (D)	$D = 1 - \frac{V_{PV}}{V_{DC}}$	0.3846
Input Inductance (L_{IN})	$L_{IN} = \frac{V_{PV}\,D}{2\Delta i_1 f_{sw}}$	0.6125mH
Small DC link Capacitors (C_{DC})	$C_{DC} = \frac{P_{pv}}{2\omega\Delta V * V_{DC}}$	2.55 µF
HFT Turn ratio		1:8
Magnetizing Inductance of HFT		0.7mH:25.2mH

Where,

ω = Switching Frequency of High frequency Transformer

ΔV = Input voltage ripple (about 3%)

Δi_1 = Input current ripple (about 10 %)

V_{DC} = Small DC link voltage

The waveforms for idealized transformer are presented in Fig. 5.4. When MOSFET switch S_1 is ON and S_2 is OFF, primary voltage (V_{r1}) is equal to the voltage across first capacitor (V_{C1}). If MOSFET switch S_2 is ON and S_1 is OFF then the primary voltage (V_{r1}) of HFT is equal to the voltage across second capacitor (V_{C2}). At steady state the volt sec of transformer is balanced for primary and secondary both.

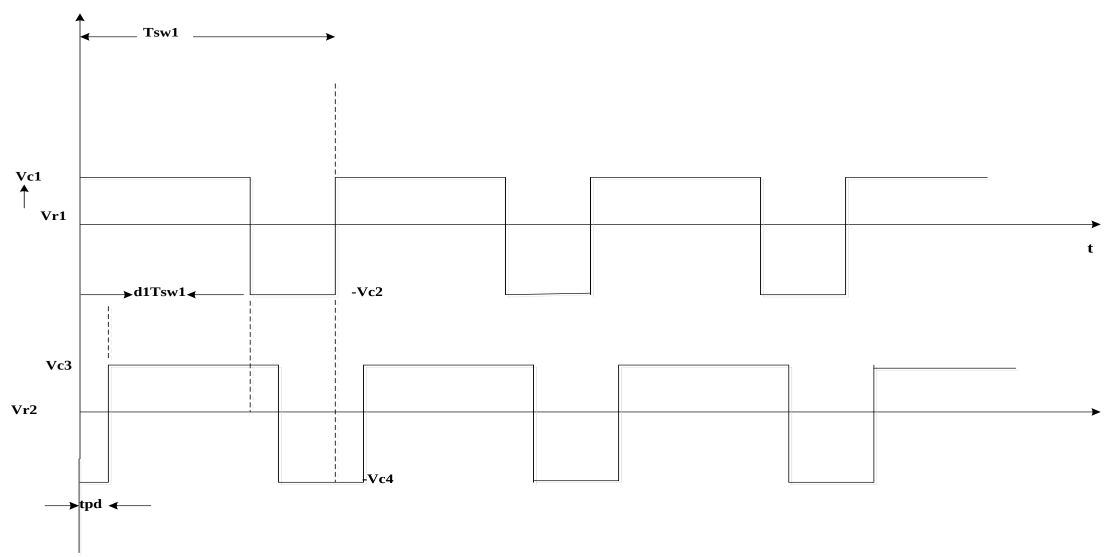


Fig. 5.4 Input/Output waveform of HFT

5.3.3Modeling of H-bridge Inverter

The main function of the inverter is to ensure that the PV modules are operated at the maximum power point (MPP) by ably supporting the DC converters. The other is to inject a near sinusoidal current into the grid with fewer harmonics [54-64]. The inverters can be operated in two modes such as

1. Square wave inverters
2. PWM inverters of following types

- Single pulse width modulation
- Multiple pulse width modulation
- Sinusoidal pulse width modulation
- Modified Sinusoidal pulse width modulation

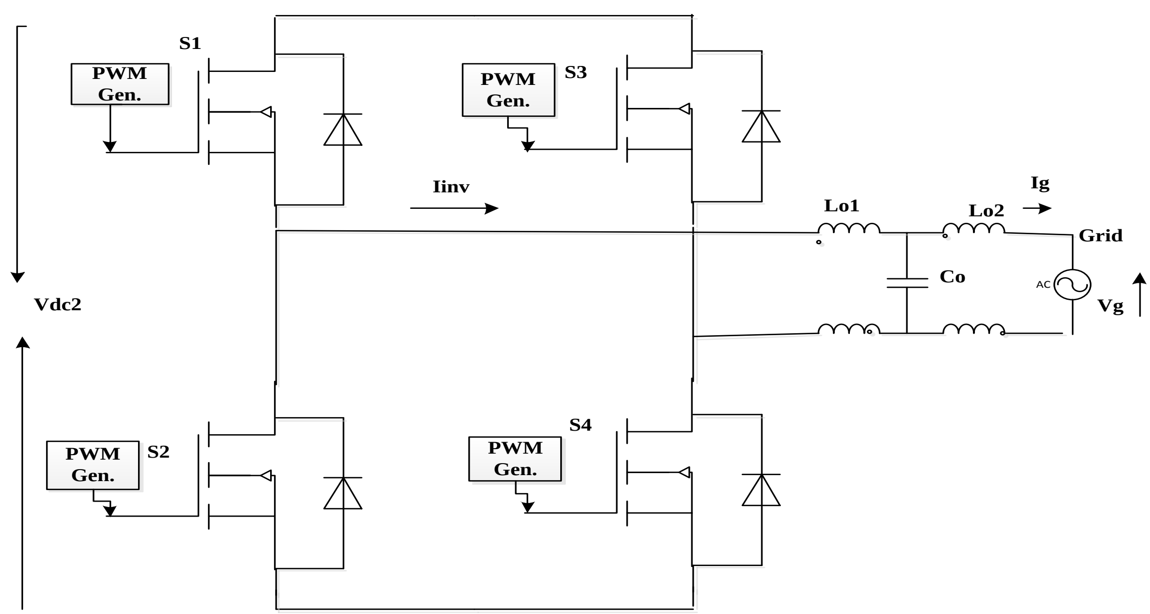


Fig. 5.5 Single phase grid connected H-bridge inverter with LCL Filter

A filter is required to integrate the PV system into grid via a single phase inverter. Main functions of filter are to convert the voltage in current from switches, reduce high frequency noise and protection of semiconductor switches from disturbances. A LCL filter is designed for this work at the output stage of single phase inverter to feed the PV power into the grid. Basically, LCL filters are the third order filter and has attenuation of -60dB/decade for value of frequencies other than resonance.

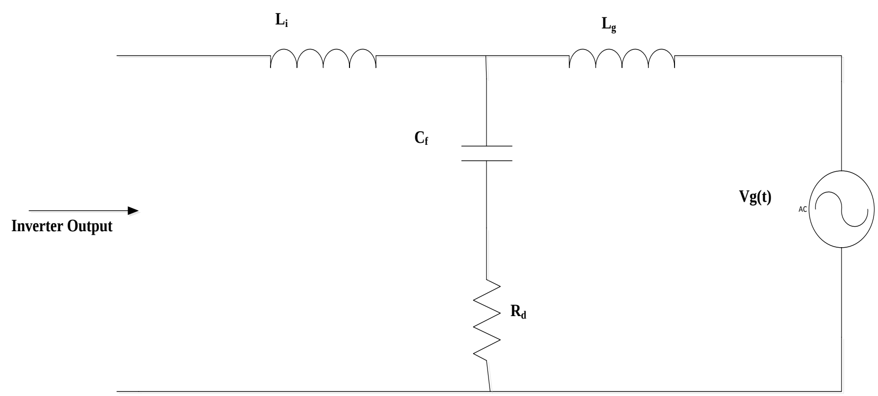


Fig. 5.6LCL Filter

Table 5.3 Parameter calculations for LCL filter

Parameter	Formula	Value
Inverter Switching Frequency (f_{sw1})		10 kHz
Grid frequency (F)		50 Hz
Grid power factor		1
Inverter side inductor (L_{in})	$L_{in} = \frac{V_{DC}}{16 f_{sw1} \Delta i_L}$	16.33mH
Grid side inductor (L_g)	$L_{g=}$r $* L_{in}$	9.798 mH
Filter capacitance (C_f)	$C_f = 0.05 * \frac{P_g}{\omega g * Ugrid}$	75.25 µF
Damping Resistance (R_d)	$R_d = \frac{1}{3\omega o * \Delta i_L C_f}$	0.03 Ω

5.3.4MPPT controller

Variable step size perturb and observe MPPT algorithm is used in this work to track the maximum power point of PV system. This algorithm divides the dP_{pv}/dV_{pv} curve of PV panel into three separate zones. Zone 0 means the PV power is close to maximum power point. A fine vale of tracking step size is used in zone 0 while zone 1 and zone 2 require a large value of step size in order to obtain a high tracking speed.

Detailed operation of given algorithm can be explained further by using flowchart given in Fig. 5.6. Δv_{ref0}, Δv_{ref1} and Δv_{ref2} represent different step sizes in zone 0, zone 1 and zone 2 respectively, k denotes the iteration count. Δv_{ref0}, Δv_{ref1} and Δv_{ref2} is taken as 0.1 V, 0.3 V and 0.3 V respectively.

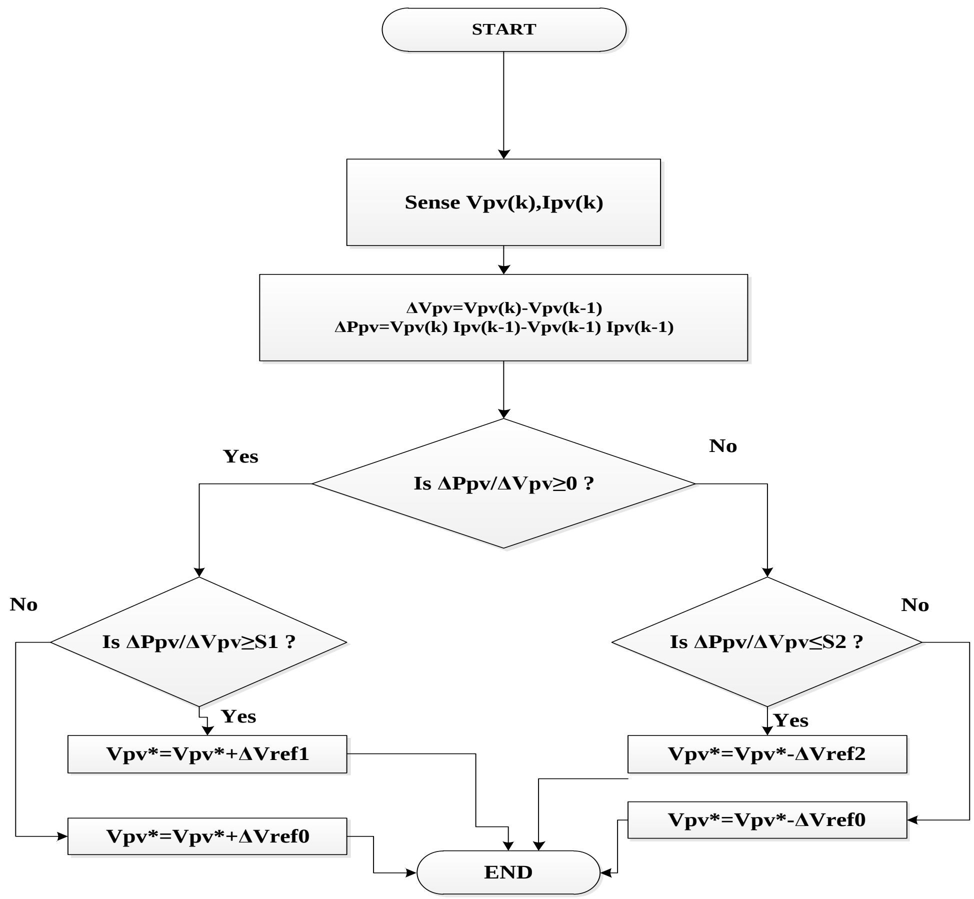


Fig. 5.7 Flowchart of variable step size P & O MPPT algorithm

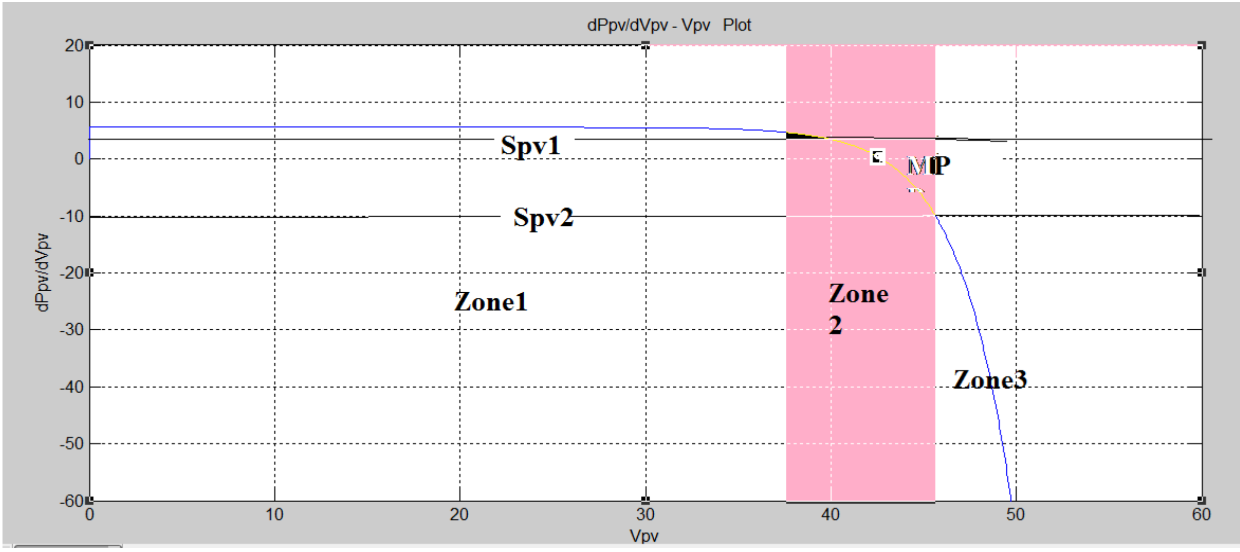


Fig. 5.8PV operation zone separation based on dP_{pv}/dV_{pv}

5.4 SIMULATION RESULTS WITH DIFERENT CONTROL SCHEMES

The Fig. 5.9 shows the simulation model of the solar PV system with half bridge converter. In this model, the Simulink based solar PV module as input with MPPT. The input capacitor forms the voltage divider circuit and the MOSFET switches are switched as per the MPPT block. The HFT and full bridge diode rectifier provides the DC link voltage for the inverter. The inverter is SPWM switched and is controlled with the Inverter control block. It generates the SPWM signals for the H bridge inverter.

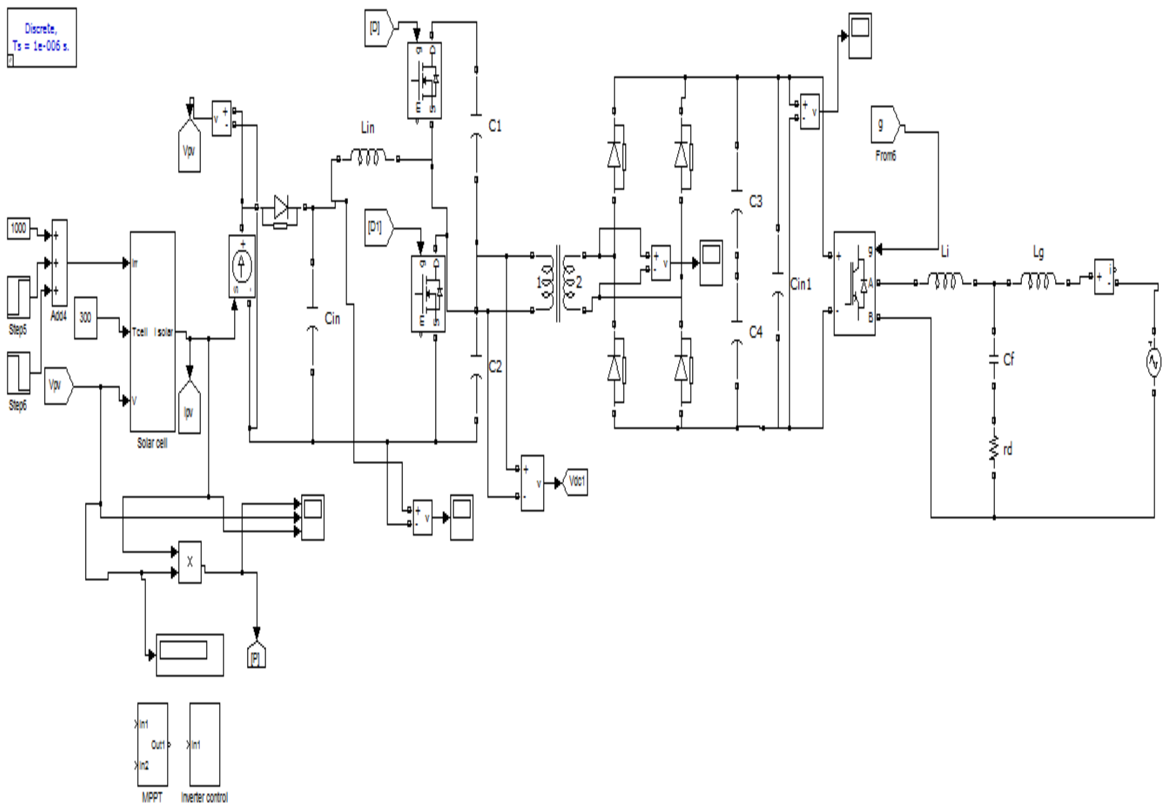


Fig. 5.9 Simulink model of single phase grid connected PV system

5.4.1Synchronous 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,

$$v_\alpha = V_m \cos(\omega t + \Phi) \quad (5.6)$$

And current are given as:

$$i_\alpha = I_m \cos(\omega t + \theta_n) \quad (5.7)$$

Following equation gives

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

i_d= In phase component of Grid current

i_q= Reactive component of Grid current

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

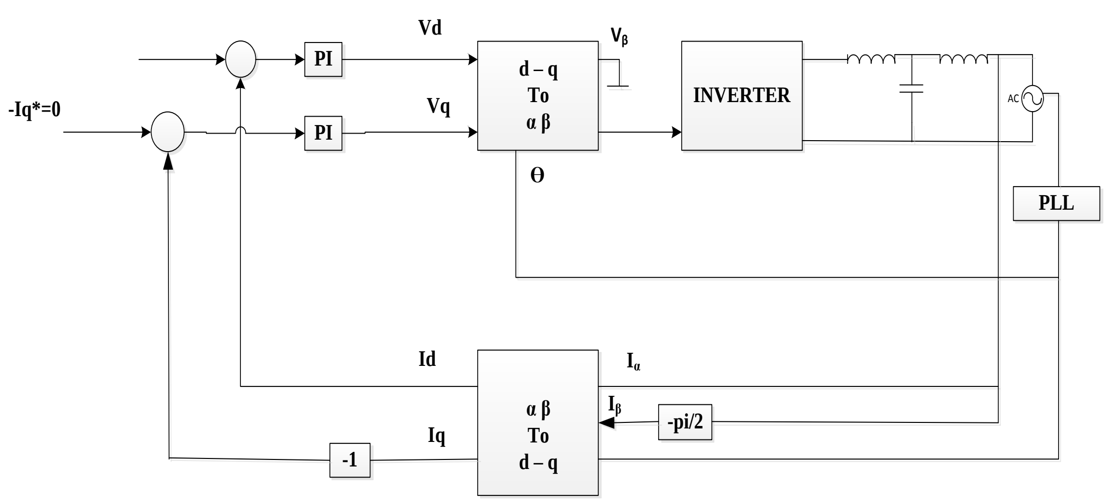


Fig. 5.10 Reference current extraction using SRF theory

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.

SRF based current controller is implemented in single phase grid connected system in order to achieve grid synchronization. Fig. 5.12 and Fig. 5.13 show the PV voltage and PV output power respectively. The PV voltage is maintained constant at 30 V, which is nearly equal to the voltage at maximum power point. The system is simulated under STC conditions. DC link reference voltage is 400 V, Fig. 5.11 shows the actual DC link voltage.

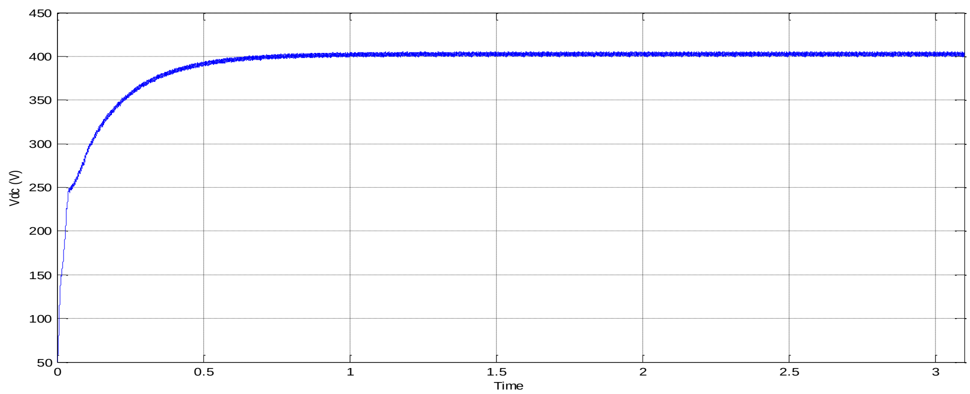


Fig. 5.11DC link voltage

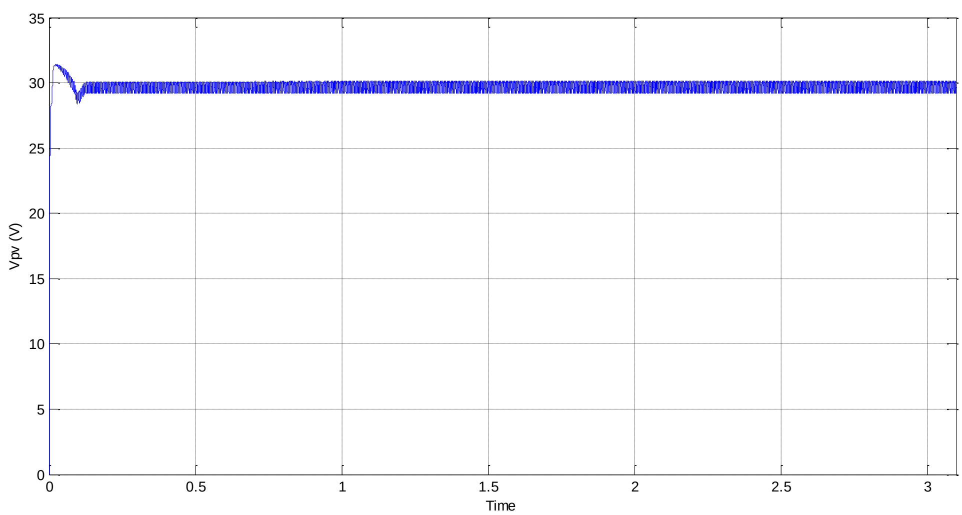


Fig. 5.12 Solar PV array output voltage

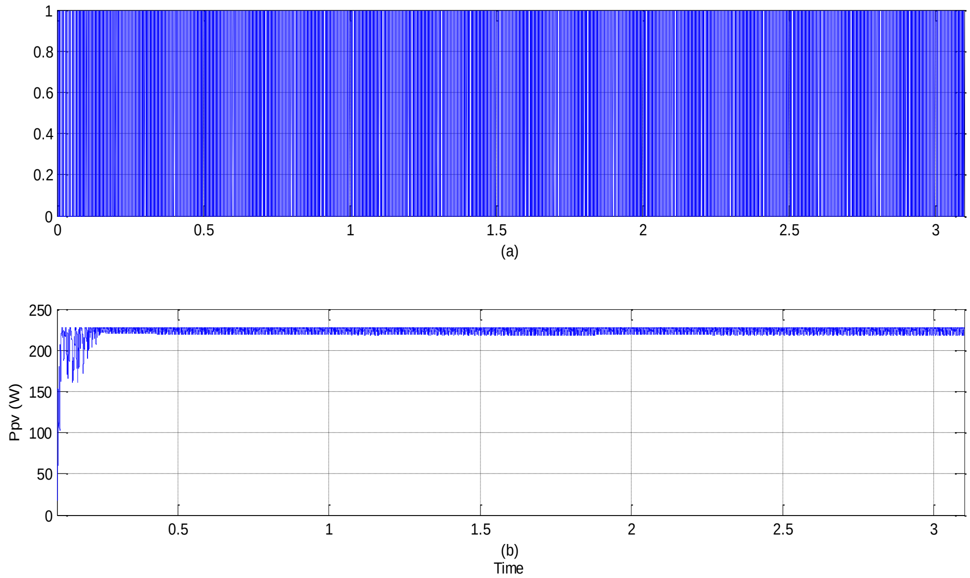


Fig. 5.13(a) pulses for DC/D C boost converter, (b) Solar PV array output power

Fig. 5.14 shows the waveform of inverter output voltage which is a unipolar waveform. Fig. 5.15, Fig. 5.16 and Fig. 5.17 shows the inverter output current, grid voltage and grid current respectively.

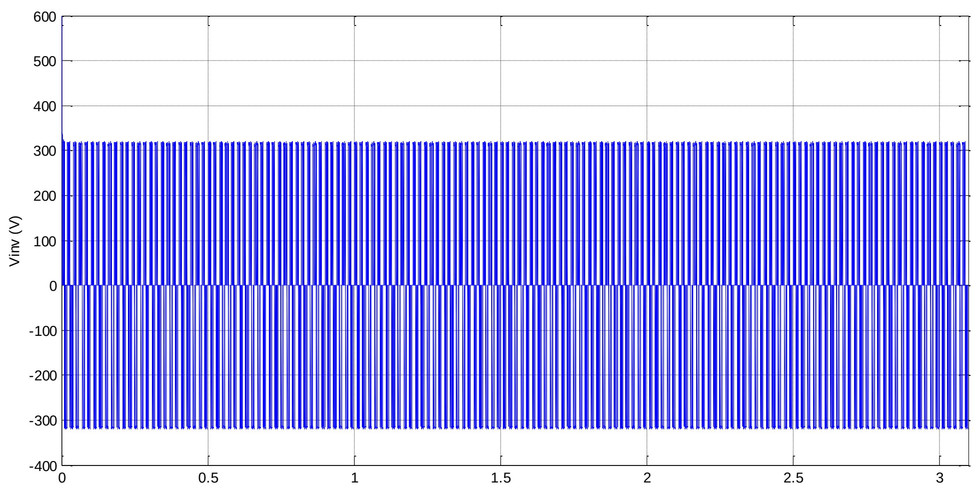


Fig. 5.14 Inverter output voltage without filtering

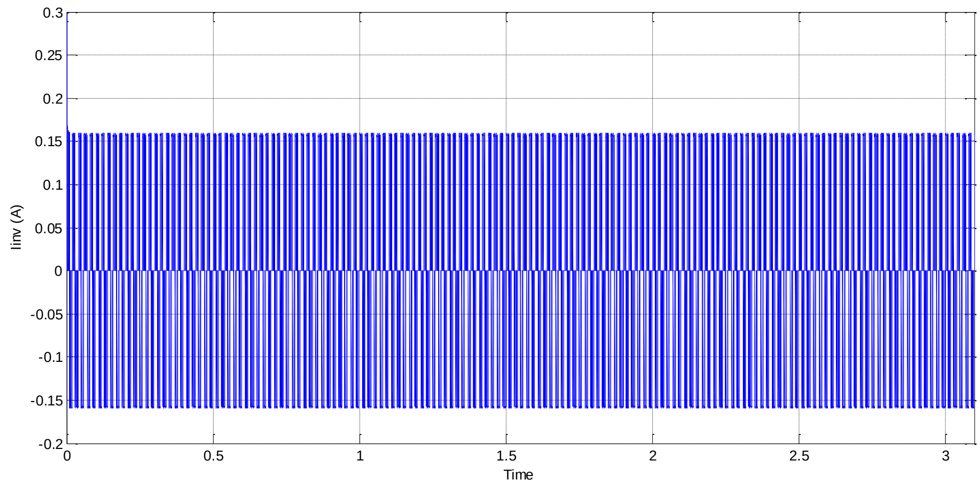


Fig. 5.15 Inverter output current without filtering

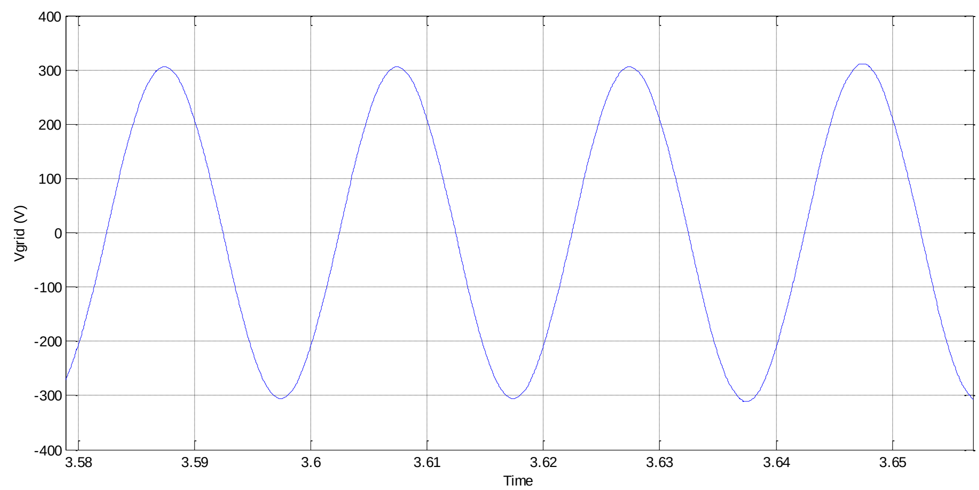


Fig. 5.16 Grid voltage (V)

5.4.2Digital PI based current controller

The PI control method can be used digitally oranalog 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.

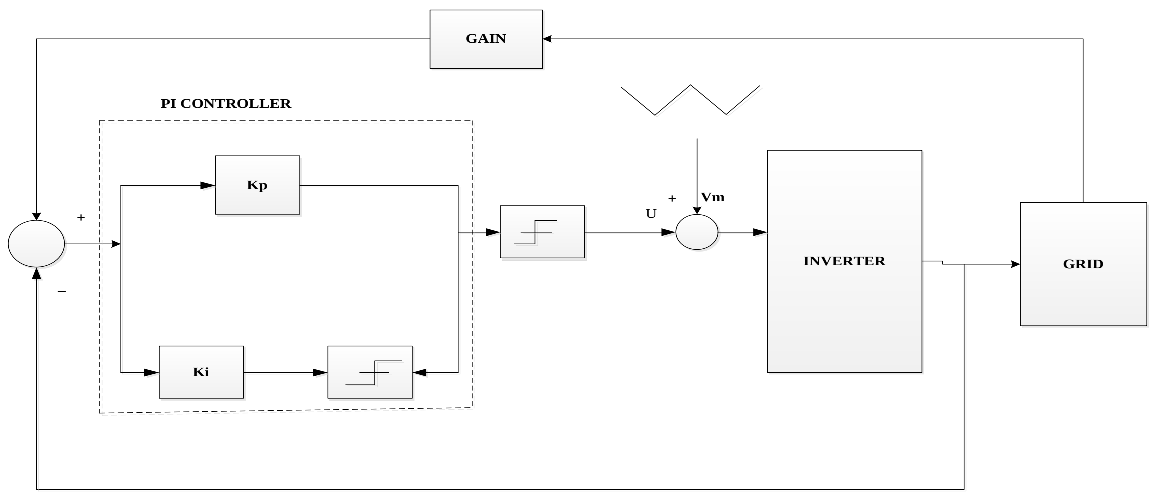


Fig. 5.17 Inverter control using PI controller

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

$$u(t) = Kpe(t) + Ki \int e(\tau)\, d\tau \quad (5.10)$$

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.

$$Kpe(t) = Kpe(k) \tag{5.11}$$

$$Ki \int_{\tau=0}^{t} e\,(\tau)\, d\tau = Ki \sum_{i=0}^{k} \frac{h}{2} [e(i) + e(i-1)] \tag{5.12}$$

$$t = k * h \tag{5.13}$$

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

$$u(k) = Kpe(k) + Ki \sum_{i=0}^{k} \frac{h}{2} [e(i) + e(i-1)] \tag{5.14}$$

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

$$sum\,(k) = sum\,(k-1) + [e(k) + e(k-1)] \tag{5.15}$$

$$u(k) = Kp\, e(k) + Ki\, sum\,(k) \tag{5.16}$$

Simulation has been done for a single phase grid connected PV system by keeping its parameters at STC. Fig. 5.18 shows the PV output voltage which is maintained at a constant value of 28 V less than the voltage at maximum power point

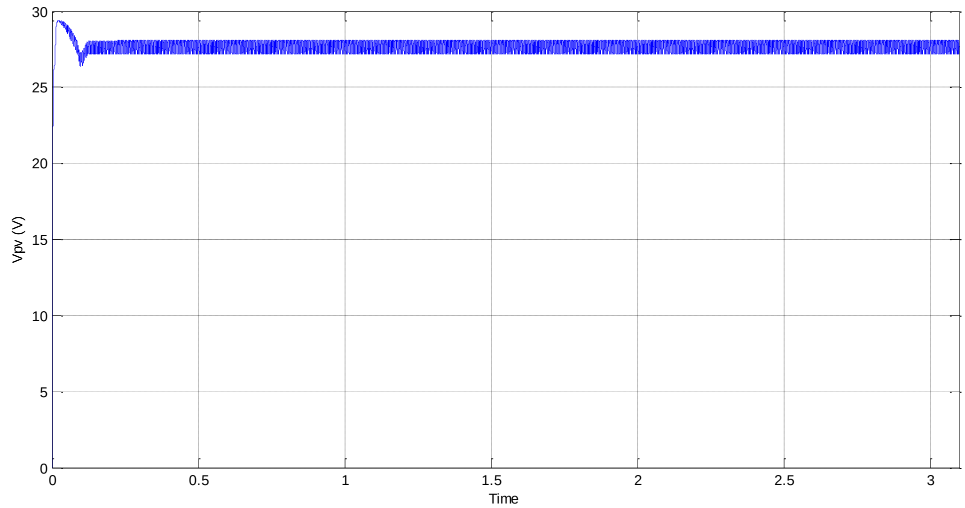


Fig. 5.18PV output voltage

This is utmost important to maintain the DC input voltage of inverter at a constant value, so that the AC output voltage remain constant and the system can be synchronized with the utility grid. Here a reference value of DC link voltage is set at 400 V. In this case the DC link voltage is 380 V approximately and has a constant value throughout the simulation period.

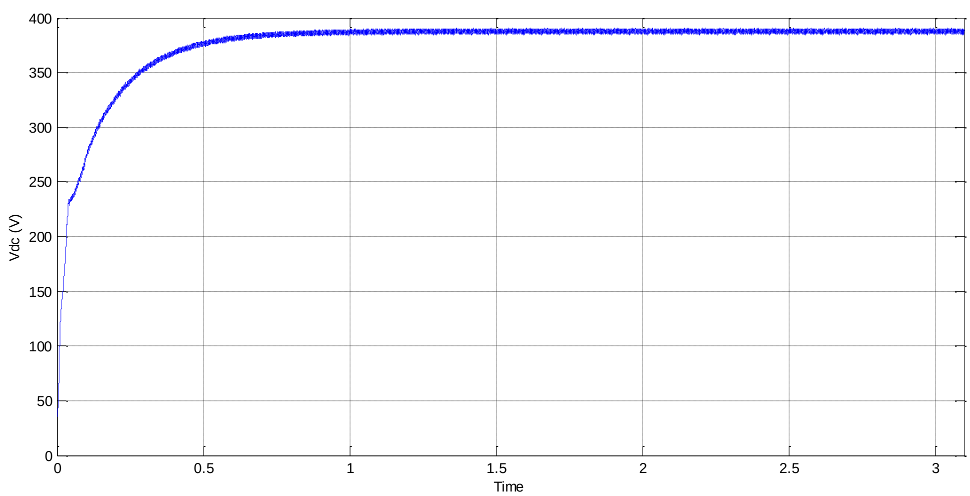


Fig. 5.19DC link voltage (V)

Fig. 5.20 shows the waveform of the grid voltage and Fig. 5.21grid current (I_{grid}), which is apure sinusoidal waveform in phase with the grid voltage and atunity power factor.V_{inv} is shown in Fig. 5.22 which is a unipolar square wave voltage. PI control signal iscompared with a triangular carrier signal in order to generate gating pulses for the inverterswitches.

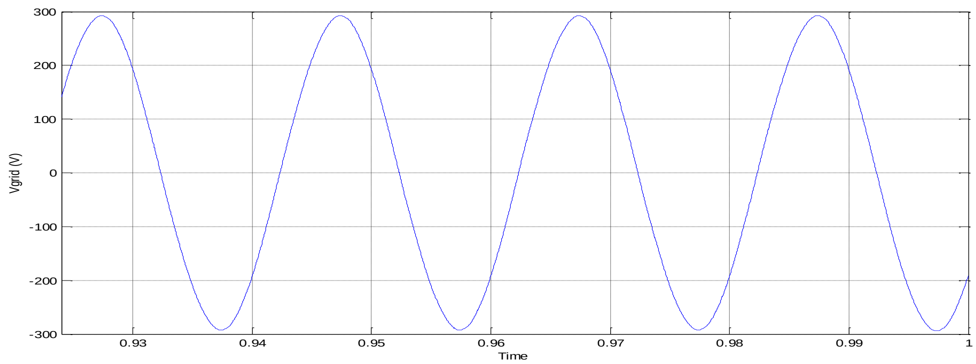


Fig. 5.20 Grid voltage (V)

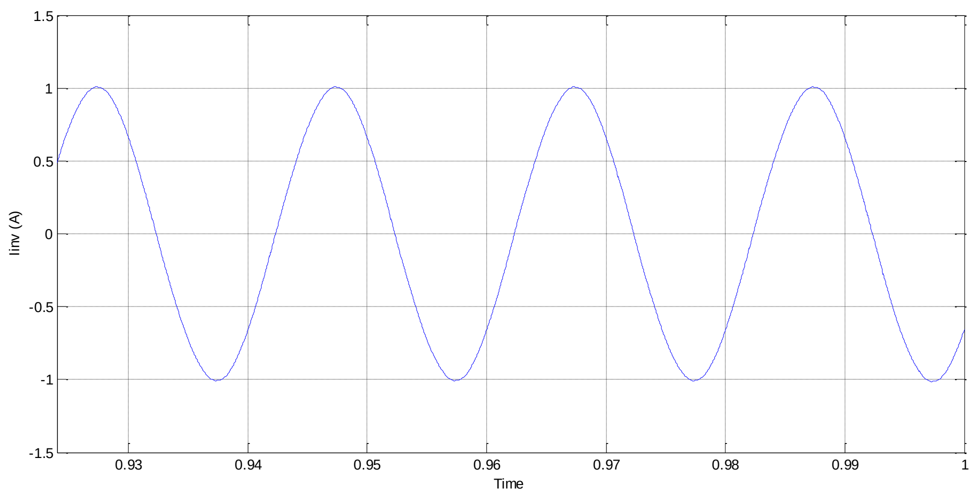


Fig. 5.21 Grid current (A)

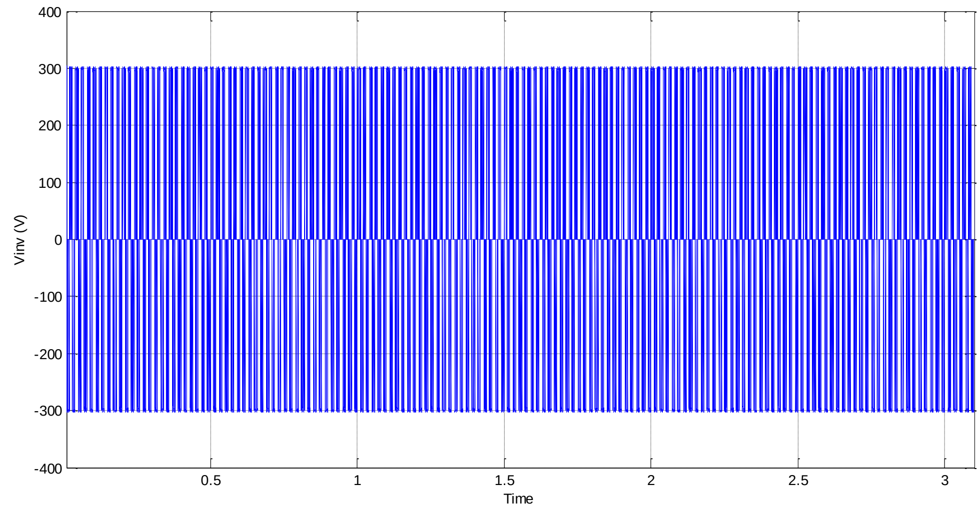


Fig. 5.22 Inverter output current (A)

5.5 CONCLUSION

This chapter presented design and modeling of single phase grid connected PV system with simulation results. Two control algorithms have been developed and implemented with the system to control the single phase inverter and to synchronize the system with utility grid.SRF based control technique is developed for single phase system with some modifications. Second control technique is basically based on a Digital PI current control method.

CHAPTER 6

DESIGN, MODELING & SIMULATION OF THREE PHASE GRID CONNECTED SOLAR PHOTOVOLTAIC SYSTEM

6.1 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. This chapter consists of detailed modeling of three phase grid connected SPV system with various control schemes.

6.2 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.

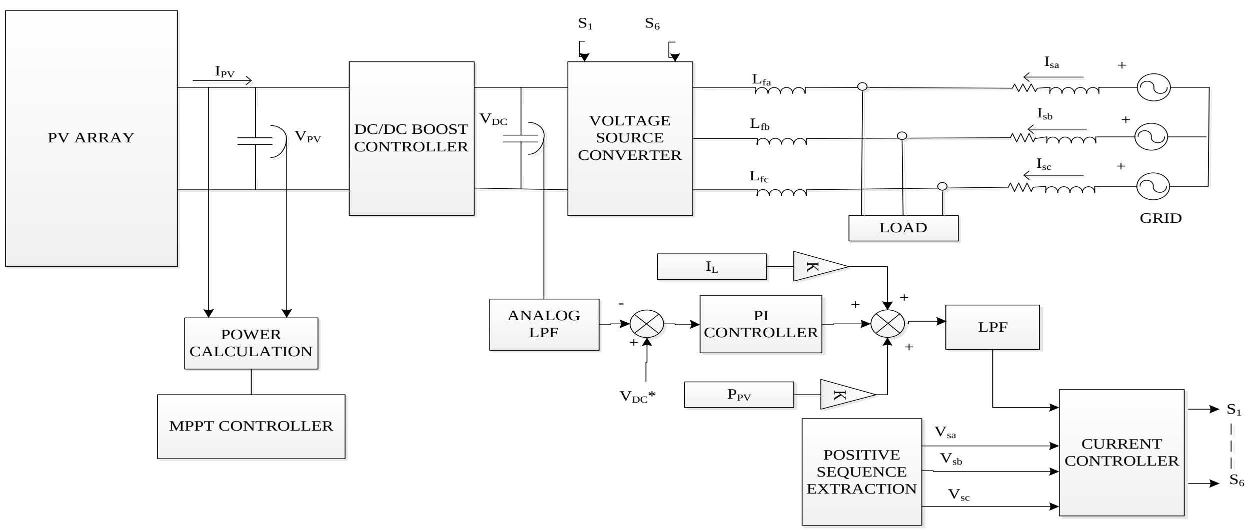


Fig. 6.1 System description

6.3 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.

6.3.1PV 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.

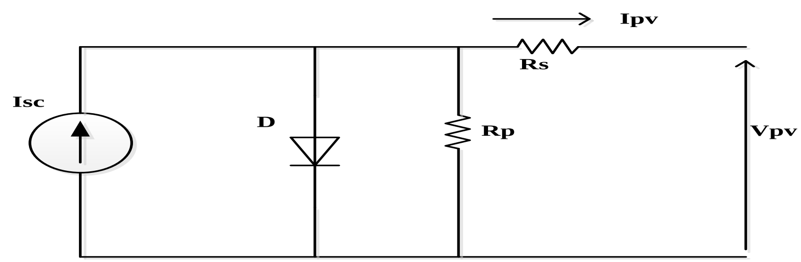


Fig. 6.2 Equivalent circuit model of solar module

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

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \quad (6.1)$$

Thus,

$$I_{PV} = I_{sc} - I_D - \frac{V_D}{R_p} \quad (6.2)$$

The reverse saturation current I_{rs} is given as

$$I_{rs} = I_{scref} + [\exp\left(\frac{qVoc}{NskAT}\right) - 1] \quad (6.3)$$

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

$$I_o = I_{rs}\left[\frac{\left(\frac{T}{T_{ref}}\right)^3 e^{qCg}}{Ak} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (6.4)$$

The basic equation that describes the current output of the PV module of the single-diode model is given in equation (5).

$$I_{PV} = I_{sc}N_p - N_s I_o\left[\exp\left\{\frac{q(V_{PV}+I_{PV}Rs)}{N_s AkT}\right\} - 1\right]V_{PV} + \frac{I_{PV}Rs}{Rp} \quad (6.5)$$

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.

6.3.2DC/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.

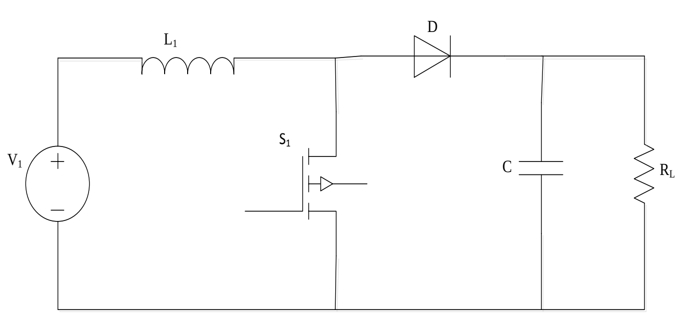


Fig. 6.3 Equivalent circuit model of DC/DC boost converter

Table 6.1 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)	$\mathrm{D} = 1 - \frac{V_{PV}}{V_{DC}}$	0.375
Input Inductance (L_1)	$L_1 = \frac{V_{PV}\ \mathrm{D}}{2\Delta i_1 f_{sw}}$	1.5 mH
DC link Capacitors (C)	$C = \frac{I_{in}\mathrm{D}}{\Delta v f_{sw}}$	2800µF

Where,

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

Δi_1 = Input Current ripple (about 10%)

Δv = Input voltage ripple (3 %)

6.3.3Voltage source converter

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. Fig. 6.4 shows a circuit representation of three phase voltage source converter.

Table 6.2 Parameter calculations for voltage source converter

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

Where,

VA= Load Power/Power factor

V_o = Output voltage (Line to line)

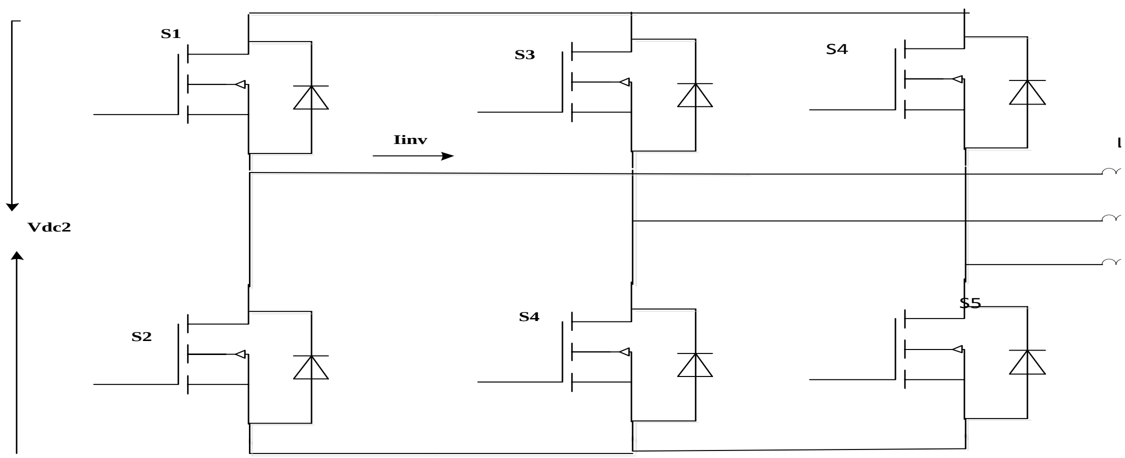


Fig. 6.4 Circuit representation of voltage source converter

6.3.4MPPT 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 Fig. 6.5.

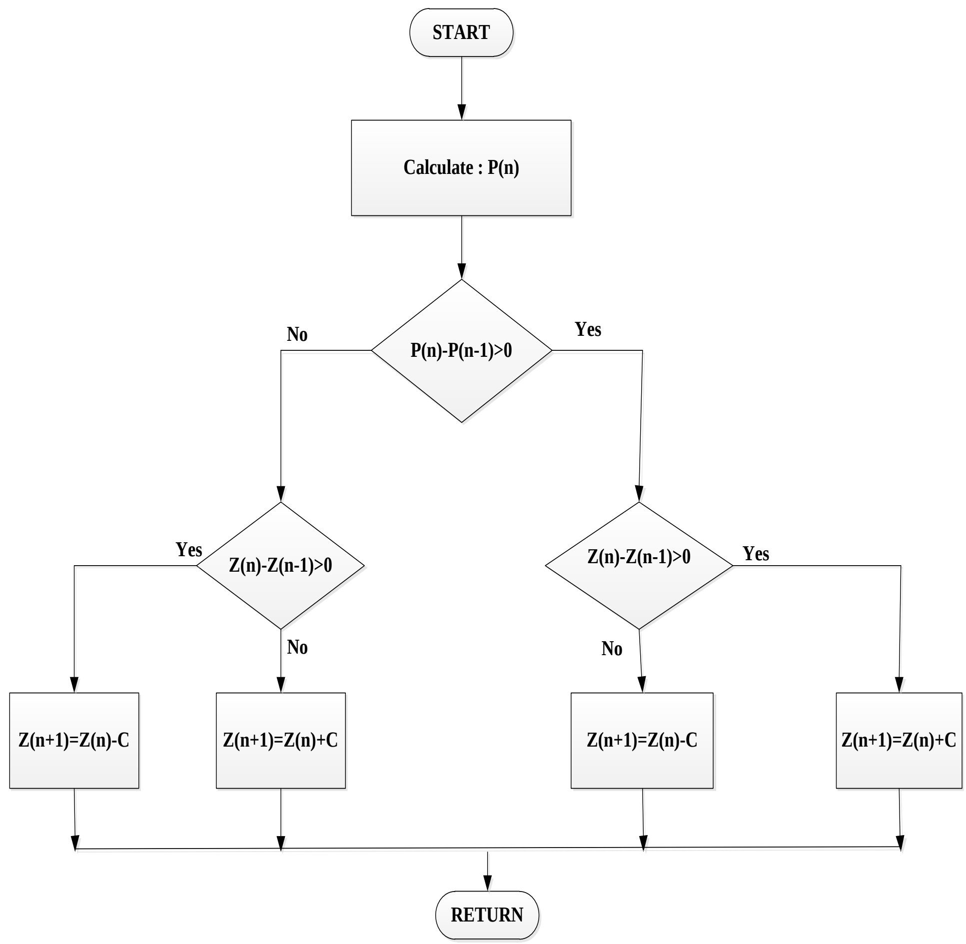


Fig. 6.5 Flowchart for Perturb & Observe MPPT technique

6.4 SIMULATION RESULTS WITH CONTROL ALGORITHM

A large number of control techniques are reported in literature for voltage source converters (VSC) like Synchronous Reference Frame theory (SRFT), Instantaneous Reactive Power Theory (IRPT), PI controller based algorithms, Adaline based algorithm etc. In present work adaptive notch filter based control technique is proposed for VSC in SPV generation system.

6.4.1Adaptive 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 in this paper. The complete system has been designed, developed and simulated by using Sim Power System and Simulink toolbox of MATLAB.

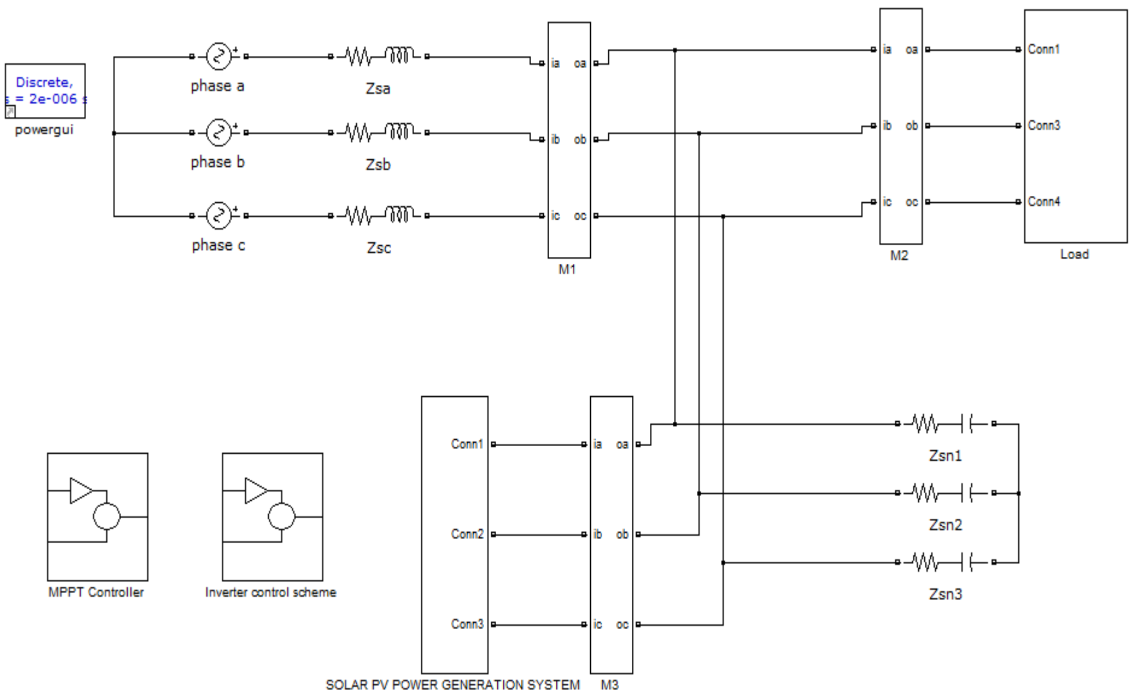


Fig. 6.6MATLAB/Simulink model of PV generation system with control algorithm

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

$$u(t) = \sum_{i=1}^{n} A_i \sin \varphi_i \quad where \;\; \varphi_i = \omega_i + \varphi_i(1)(6.6)$$

Where $A_i$non zero amplitudes, ω_i 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:

$$\ddot{x} + \theta^2 x = 2\zeta\theta e(t) \quad (6.7)$$

$$e(t) = u(t) - \dot{x} \quad (6.8)$$

$$\dot{\theta} = -\gamma\theta x e(t) \quad (6.9)$$

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

$$u(t) = A_1 \sin(\omega_1 t + \delta) \quad (6.10)$$

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

$$v(t) = \begin{pmatrix} x \\ \dot{x} \\ \theta \end{pmatrix} = \begin{pmatrix} -\frac{A_1}{\omega_1}\cos(\omega_1 + \delta) \\ A_1 \sin(\omega_1 + \delta) \\ \omega_1 \end{pmatrix} \quad (6.11)$$

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

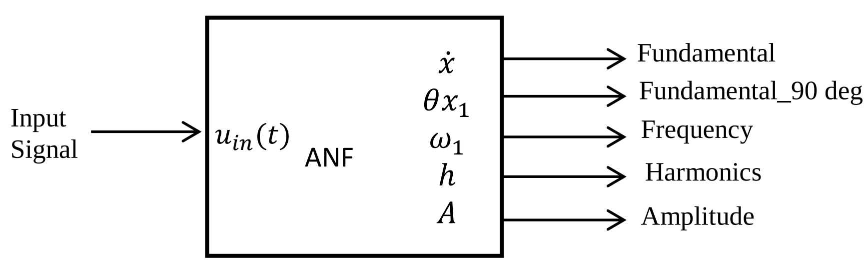


Fig. 6.7 Basic block of adaptive notch filter

6.4.2Simulation results with nonlinear load

Performance analysis of three phase grid connected solar photovoltaic system has been carried out on the basis of various parameters: PV output power, PV voltage, PV current, DC link voltage, PCC voltage, grid voltage, grid current, voltage source converter current, power supplied by the voltage source converter etc. System is designed at a voltage level of 415V (L-L). A nonlinear load of 40 kW is used for simulation studies. The maximum power output of designed SPV array is 25 kW. At 0.15 s MPPT control is applied to the system to feed maximum power to the load. Reference value of the DC link voltage is kept 700 V. Fig 6.8 shows the PV characteristics and DC link voltage is shown in Fig. 6.9. Grid voltage and grid currents are shown in Fig. 6.10 and 6.11 respectively. It can be clearly observed from the waveform that the initially the complete load current is feeding by the source only. But after 0.1 s, the load current is shared in between grid and SPV system.

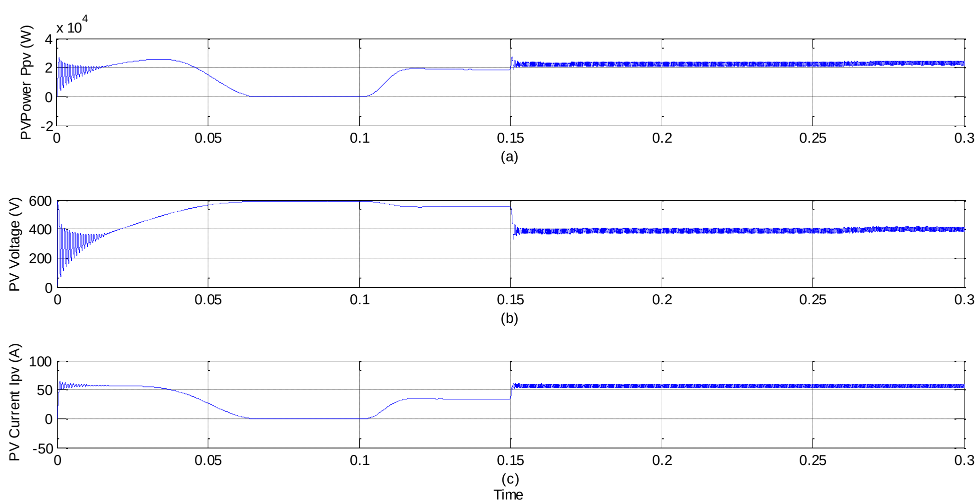


Fig. 6.8 Soar PV array characteristics (a) Power, (b) Voltage, (c) Current

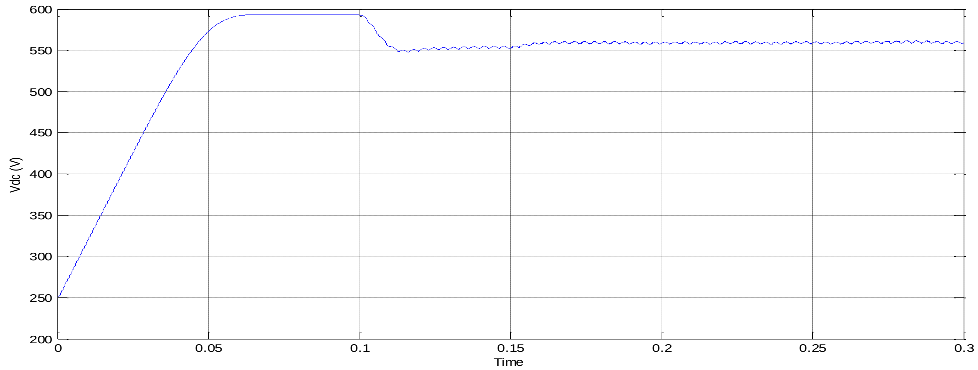


Fig. 6.9 DC link voltage (V)

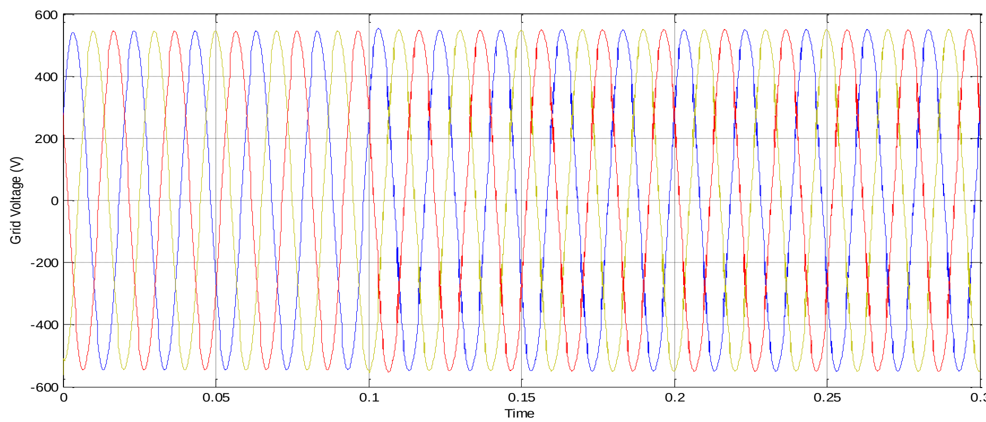


Fig. 6.10 Grid side voltage (V)

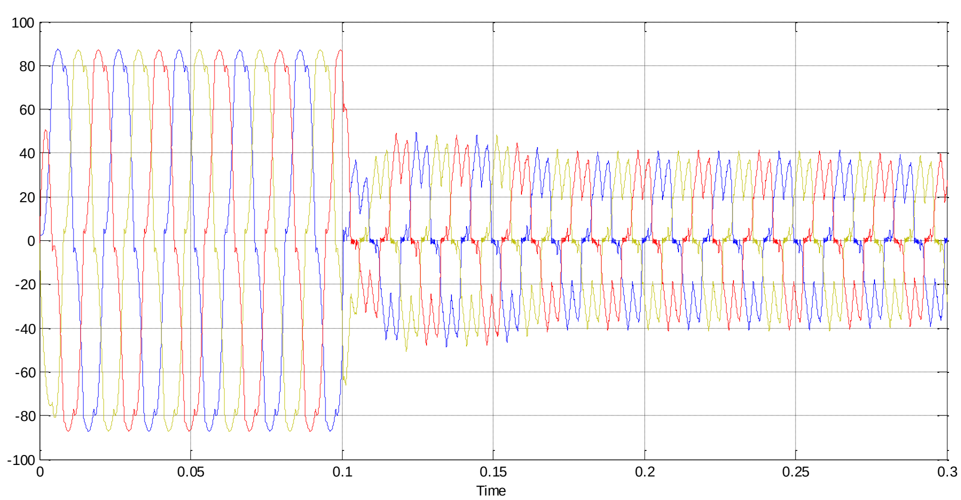


Fig. 6.11 Source current (A)

PCC voltage is shown in Fig. 6.12 with the positive extracted component of PCC voltage. Adaptive filter based approach is utilized here to extract the positive component of PCC. Load current waveforms are also shown in Fig 6.13.

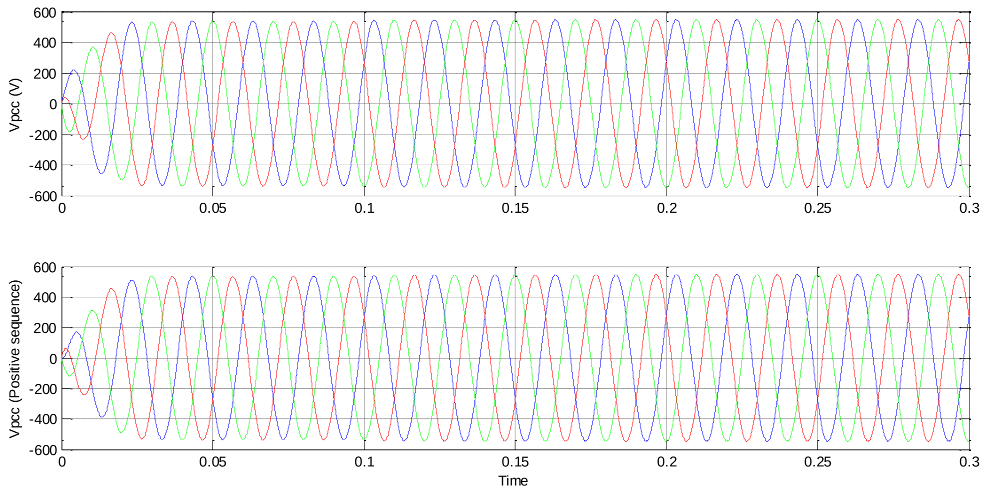


Fig. 6.12 PCC voltage (a) Vpcc, (b) Positive sequence extraction of Vpcc

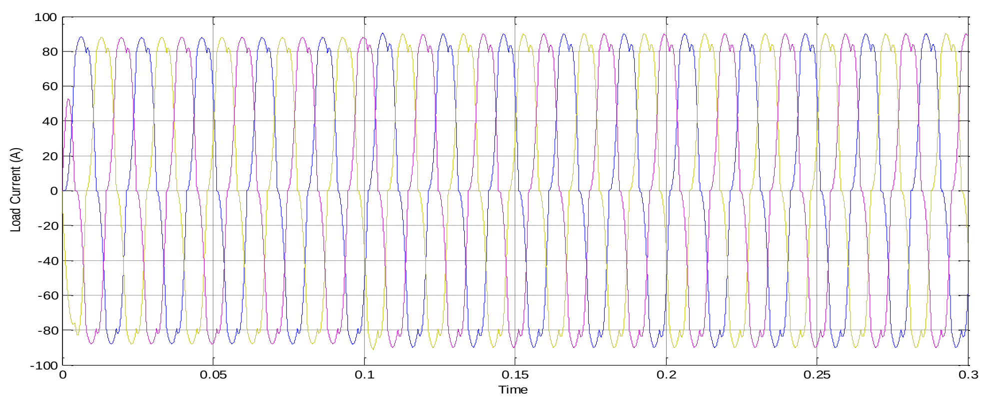


Fig. 6.13 Load current (A)

Initially the whole power requirements of the load is accomplishing by source only. After 0.1 s it is shared among the two generation sources namely grid and SPV system. Maximum amount of the reactive and active power requirement of the load is taken care by the solar photovoltaic generation system. VSC is also acting like a reactive power compensator with active power supplier. Fig. 6.14 shows the THD analysis of the source current, which is 3.75 %.

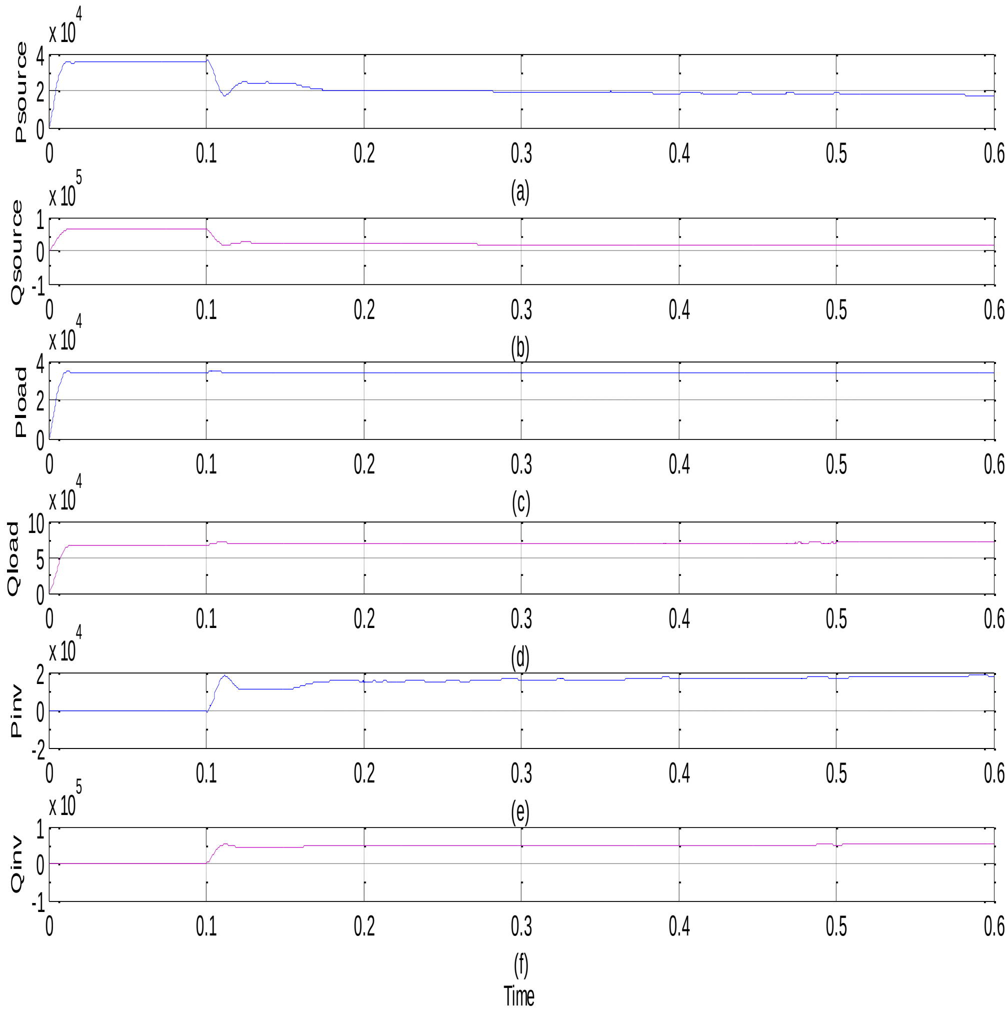


Fig. 6.14 (a) Active power delivered by source (kW), (b) Reactive power delivered by source (kVAR), (c) Active power required by load (kW), (d) Reactive power required by source (kVAR), (e) Active power delivered by PV system (kW), (f) Reactive power delivered by source (kVAR)

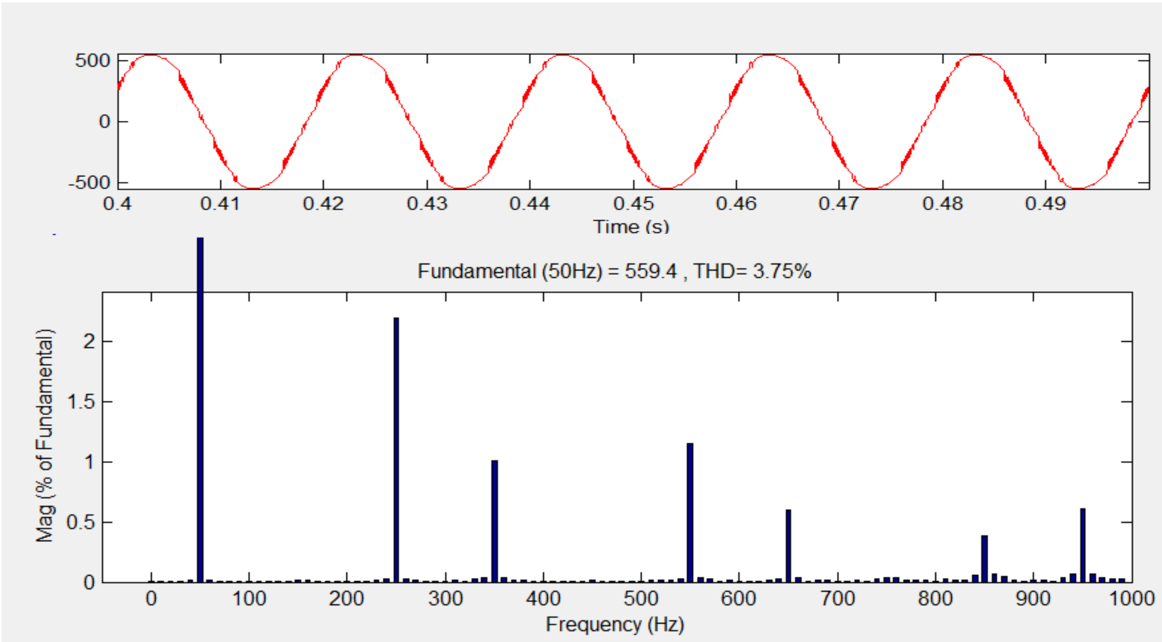


Fig. 6.15 THD of source current

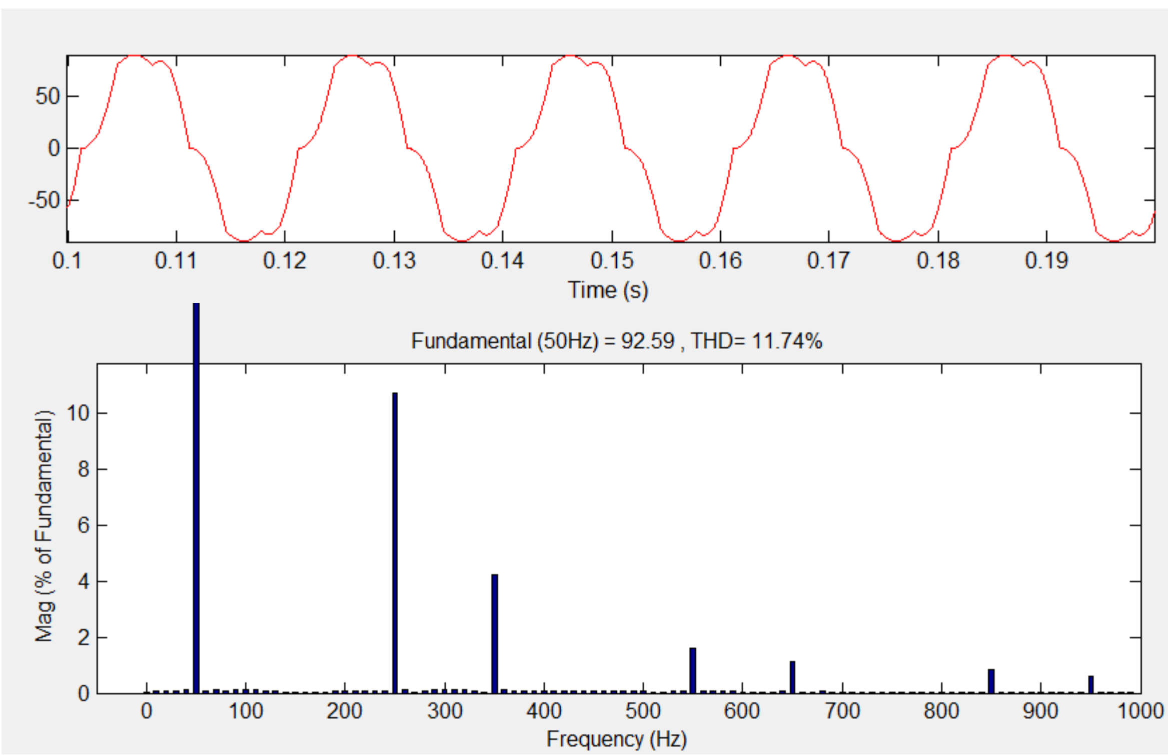


Fig. 6.16 THD of load current

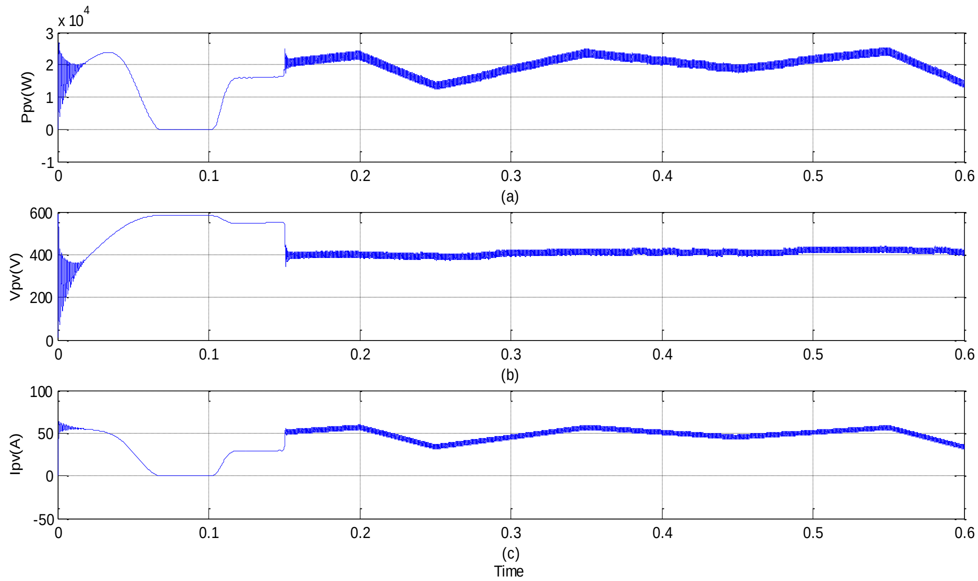


Fig. 6.17 Soar PV array characteristics for varying irradiance (a) Power, (b) Voltage, (c) Current

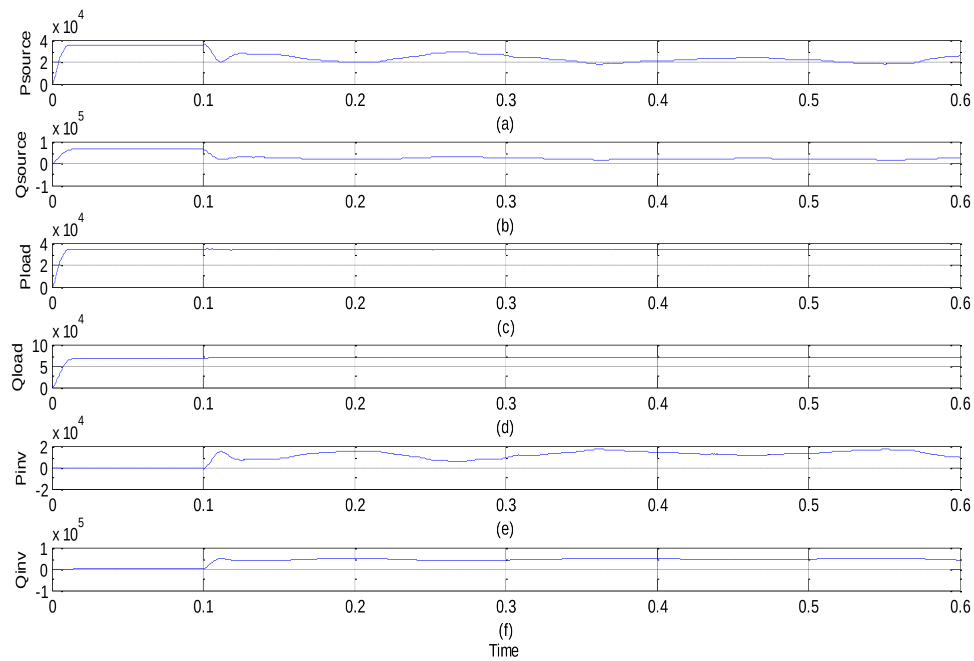


Fig. 6.18 (a) Active power delivered by source (kW), (b) Reactive power delivered by source (kVAR), (c) Active power required by load (kW), (d) Reactive power required by source (kVAR), (e) Active power delivered by PV system (kW), (f) Reactive power delivered by source (kVAR)

Fig. 6.17 shows the PV array characteristics for variations in irradiance. To visualize the effect of the changing irradiance conditions, different irradiance inputs provided to the solar PV array. Active and reactive power delver by both source and PV array along with the load requirements are shown in Fig. 6.18. When at 0.2s irradiance drops down to 800 W/m^2, output of PV system reduced. Proposed MPPT technique responds at a very fast rate in order to track the MPP of the PV array. With the drop in the output power of the PV array, output of the inverter also reduces.

6.4.3Simulation results with linear load

A linear load of 40 kW is used for simulation studies to analyze the performance of the three phase grid connected PV system. The maximum power output of designed SPV array is 25 kW. At 0.15 s MPPT control is applied to the system to feed maximum power to the load. Reference value of the DC link voltage is kept 700 V.

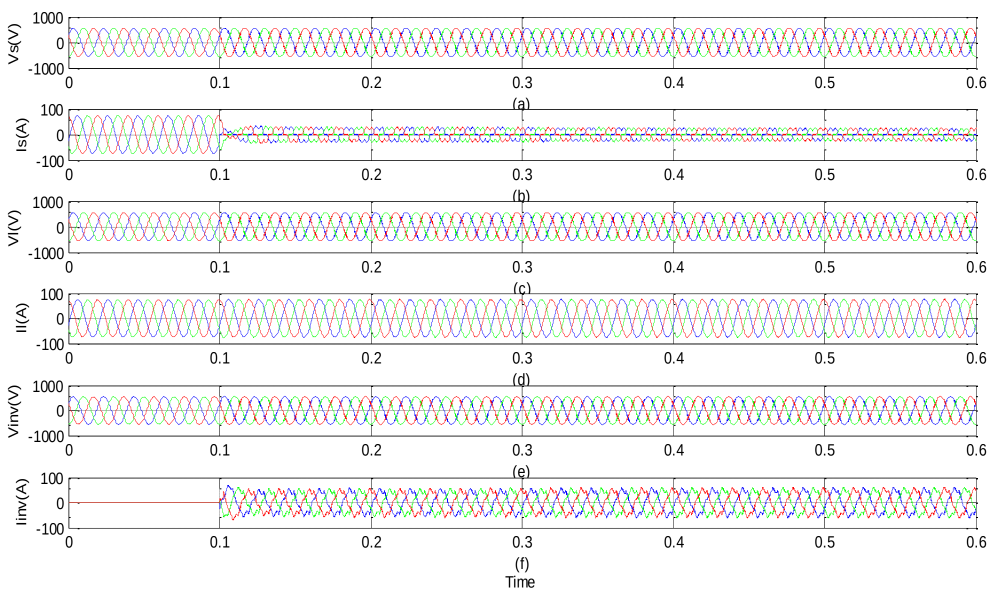


Fig. 6.19 (a) Source side voltage (V), (b) Source side current (A), (c) Load voltage (V), (d) Load current (A), (e) Inverter side voltage (V), (f) Inverter side current (A)

Grid voltage, grid current, inverter voltage, inverter current along with the load voltage and current are shown in Fig. 6.19. It can be clearly observed from the waveform that the initially the complete load current is feeding by the source only. But after 0.1 s, the load current is shared in between grid and SPV system.

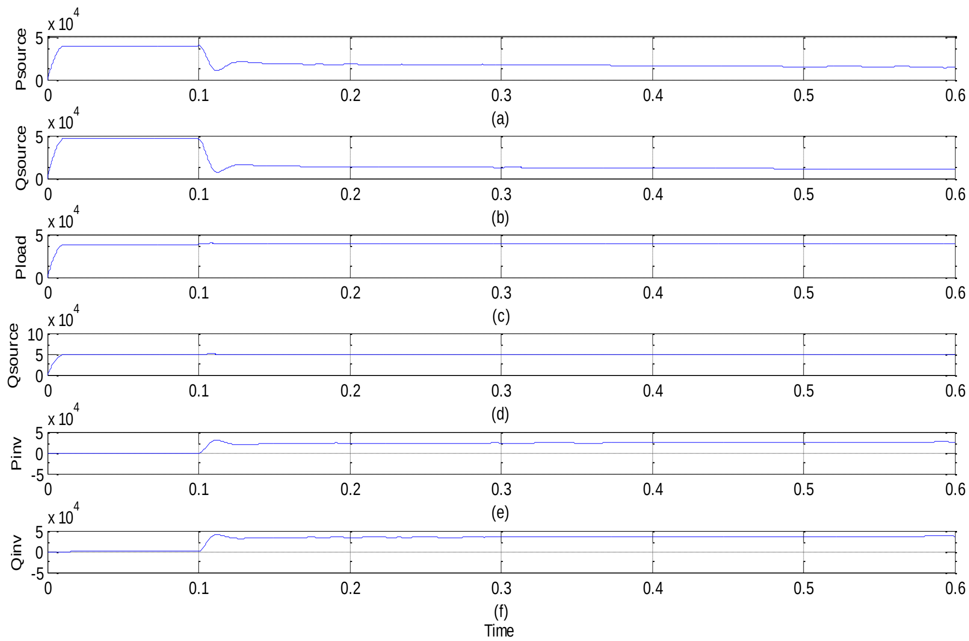


Fig. 6.20 (a) Active power delivered by source (kW), (b) Reactive power delivered by source (kVAR), (c) Active power required by load (kW), (d) Reactive power required by source (kVAR), (e) Active power delivered by PV system (kW), (f) Reactive power delivered by source (kVAR)

The total harmonic distortion analysis of source current with the integration of the PV system is 4.78 % while the THD of load current is around 0.88% only. It can be observe that the integration of solar PV array into the system increase the harmonic components in the source current is increased.

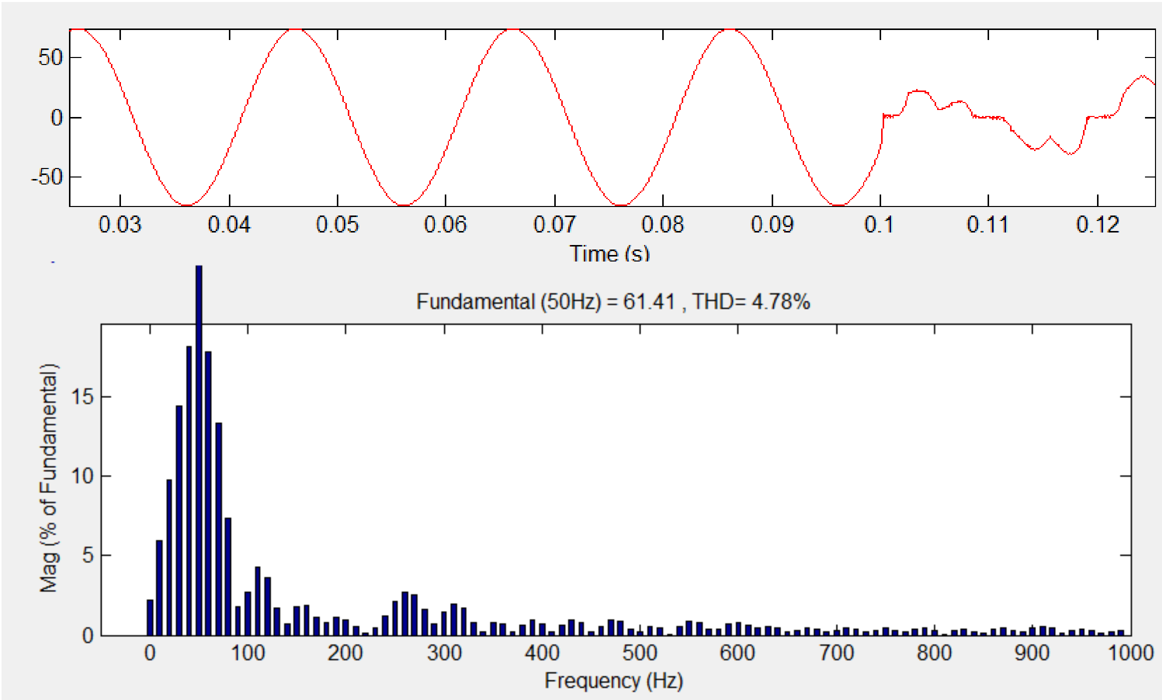


Fig. 6.21 THD of source current

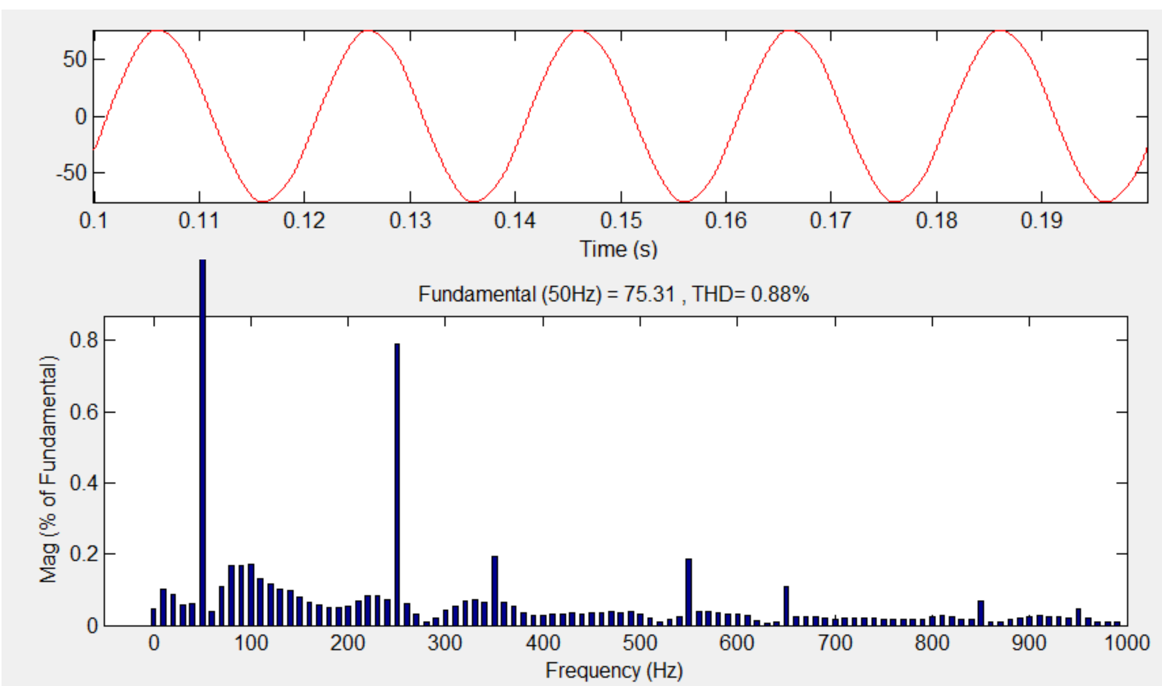


Fig. 6.22 THD of load current

In this case also to check the reliability and tracking speed of the proposed MPPT technique, changes in irradiance has been made same as the previous case.

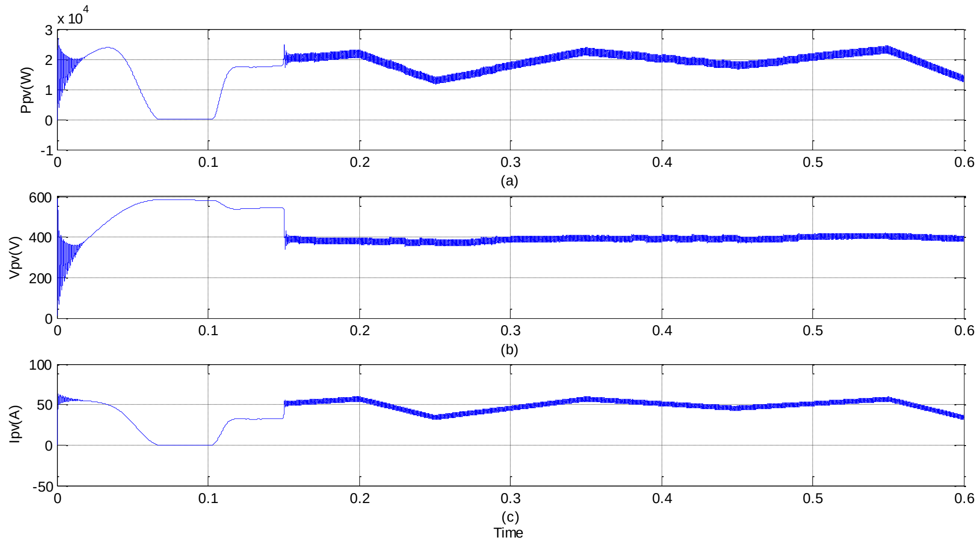


Fig. 6.23 Soar PV array characteristics for varying irradiance (a) Power, (b) Voltage, (c) Current

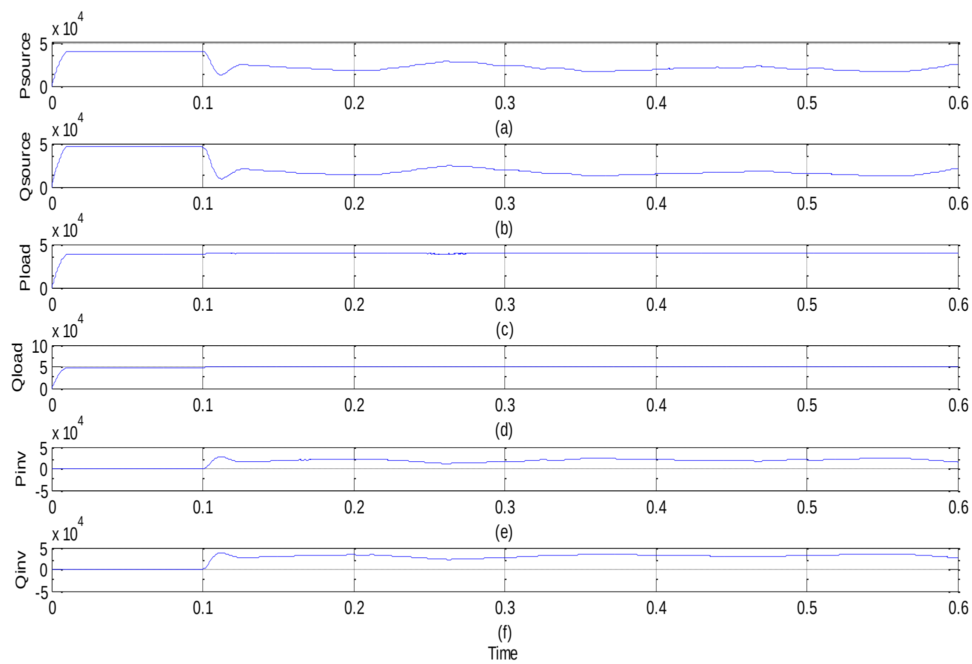


Fig. 6.24 (a) Active power delivered by source (kW), (b) Reactive power delivered by source (kVAR), (c) Active power required by load (kW), (d) Reactive power required by source (kVAR), (e) Active power delivered by PV system (kW), (f) Reactive power delivered by source (kVAR)

6.5 CONCLUSION

This chapter presented design and modeling of three phase grid connected PV system with simulation results.Adaptive notch filter based grid synchronization technique has been developed and implemented in the system to provide the control signals to the three phase voltage source converter. Simulation results are provided with proper waveforms and discussions.

CHAPTER 7

HARDWARE IMPLEMENTATION

7.1 INTRODUCTION

The main objective of this thesis is to develop the hardware for the single phase grid connected PV system using half bridge boost converter with high frequency transformer. As the output voltage of PV system is not enough to integrate this with the grid, it is necessary to modify the classical boost converter available in literature. In simulation analysis the modified converter is working satisfactorily. But the high frequency transformer is most difficult component to design and still it is under development stage. So a lab scale prototype has been developed which contains a solar PV module, DC/DC boost converter, a single phase H bridge inverter. In this chapter the hardware implementation of the solar power converter with MPPT interfaced with actual solar array controlled using dSPACE is presented.

7.2 HARDWARE DESCRIPTION

The major components of implemented hardware are:

- Vikram Solar make 250 W_p PV panel
- DC/DC boost converter
- Single phase H bridge inverter
- Measurement circuit using current and voltage sensors
- Protection circuitry
- dSPACE
- Personal computer to interface software with hardware

A detailed description of each hardware component is given in the following sections. In addition, the complete hardware is presented in Fig. 7.1.

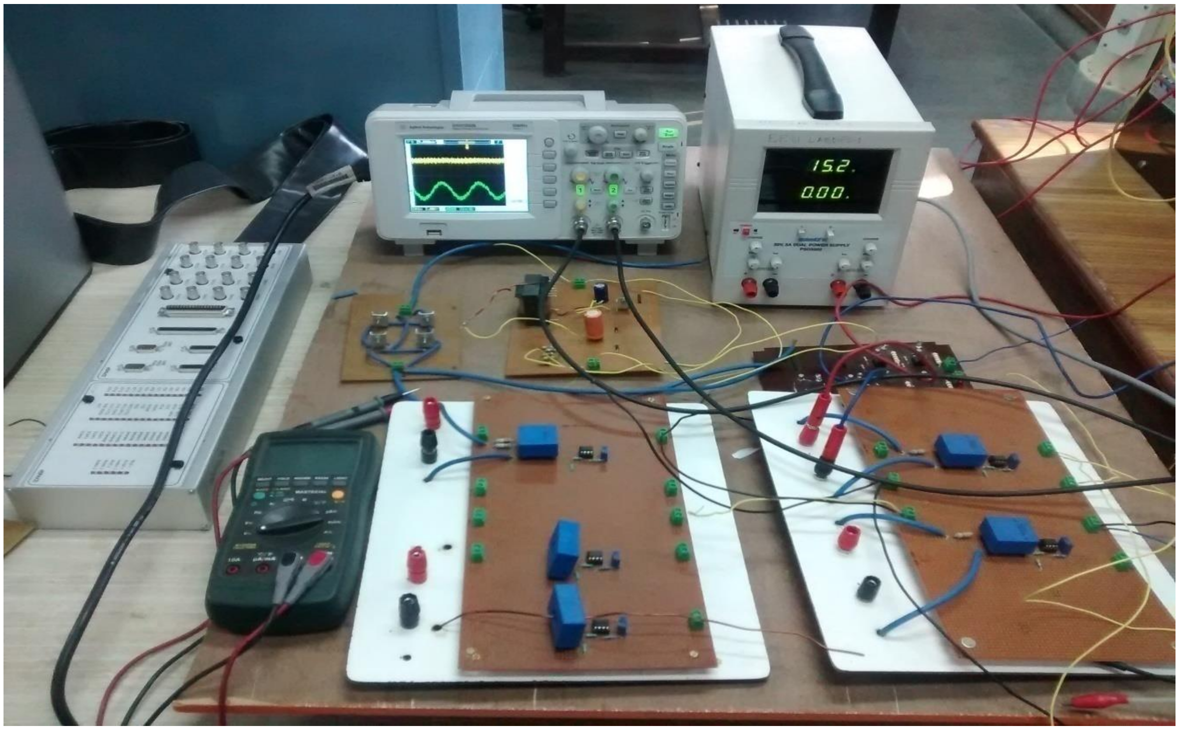


Fig. 7.1 Complete hardware system

7.3 SOLAR PV MODULE

A Vikram Solar make 250 W_p solar PV panel is used in this project. The technical specification of this panel is given in Table 5.1.

7.4 DC/DC CONVERTER

This boost configuration based DC/DC converter is built using MOSFET switch capable of higher switching frequencies. MOSFETswitch is mounted on individual heat sinks as per thermal heat dissipation requirement. The design details of the DC/DC converter are as given in the Fig. 7.2. The PWM pulses generated from dSPACE and are fed to the gate of the MOSFET through the isolation and amplifier circuit.

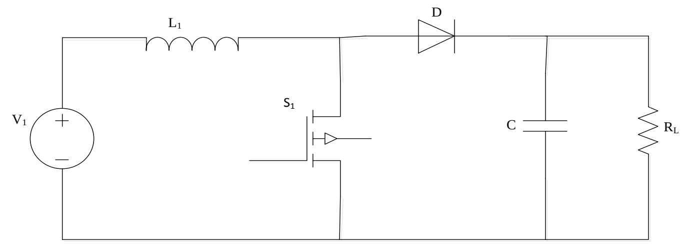


Fig. 7.2 DC/DC boost converter

7.5 MEASUREMENT UNITS

A sensor is a device which converts measured physical quantity into a form of signalrequired by the end instrument. Current and voltage of converter are measured by the current (LEM LA 25 P) and voltage (LEM LV 25 P) respectively. These currents and voltage values are input to dSPACE system. Output of these sensors are small amount of current, so a resistance is added in series to the sensor and voltage drop across it is taken as the input to dSPACE.

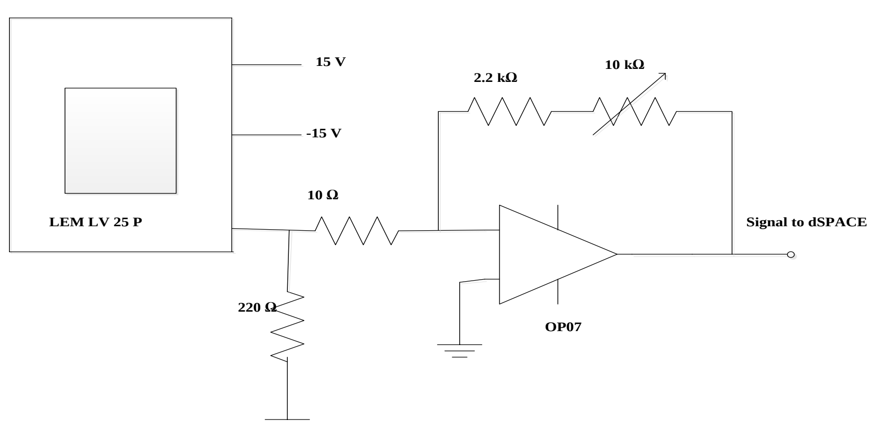


Fig. 7.3 Sensor circuit

7.6 SNUBBER CIRCUIT FOR MOSFET SWITCHES

A snubber circuit is required to protect MOSFET switch from dV/dT protection during switching operations. The circuit is basically consists of a diode, resistance and a capacitor, which are connected across the MOSFET switches.

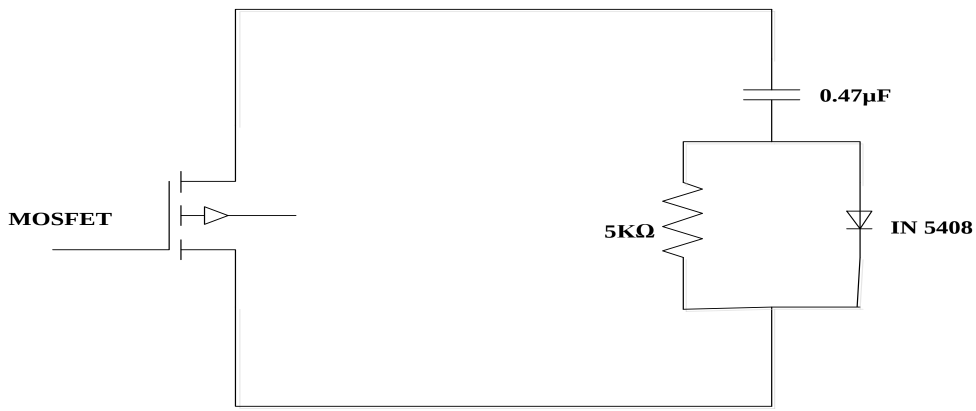


Fig. 7.4 Snubber circuit

7.7 SINGLE PHASE INVERTER

The International rectifier make insulated gate bipolar transistors (IGBT)are used as a switch of H bridge inverter in this project. These IGBT switches are capable of high power ratings (600 V, 12 A). It had internal driver gate driver and switch protection circuits against the switching transient and are capable of switching at a maximum switching frequency of 20 kHz. An isolation circuit using optocoupler is used to send the PWM signal from dSPACE to gate driver circuits.

7.8 ISOLATION AND GAIN CIRCUIT

The switching signalsgenerated from dSPACE PWM output module are applied to the optical isolation circuit consisting of the 6N136 optocoupler and its output is amplified through 2N222A switching transistor to 15V. The optocoupler provides the optical isolation between the control circuit including dSPACE and the gate power circuit. The same isolation circuit can be used for the MOSFET and IGBTs both. The isolation circuit is shown in Fig. 7.5.

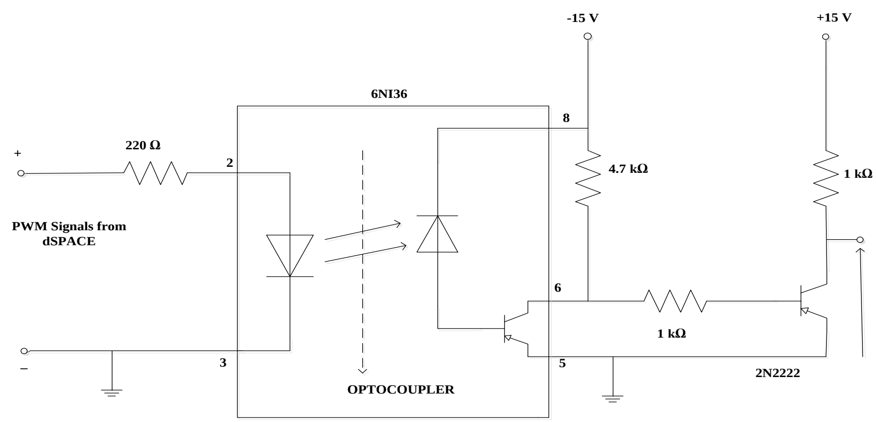


Fig. 7.5 Gate driver circuit

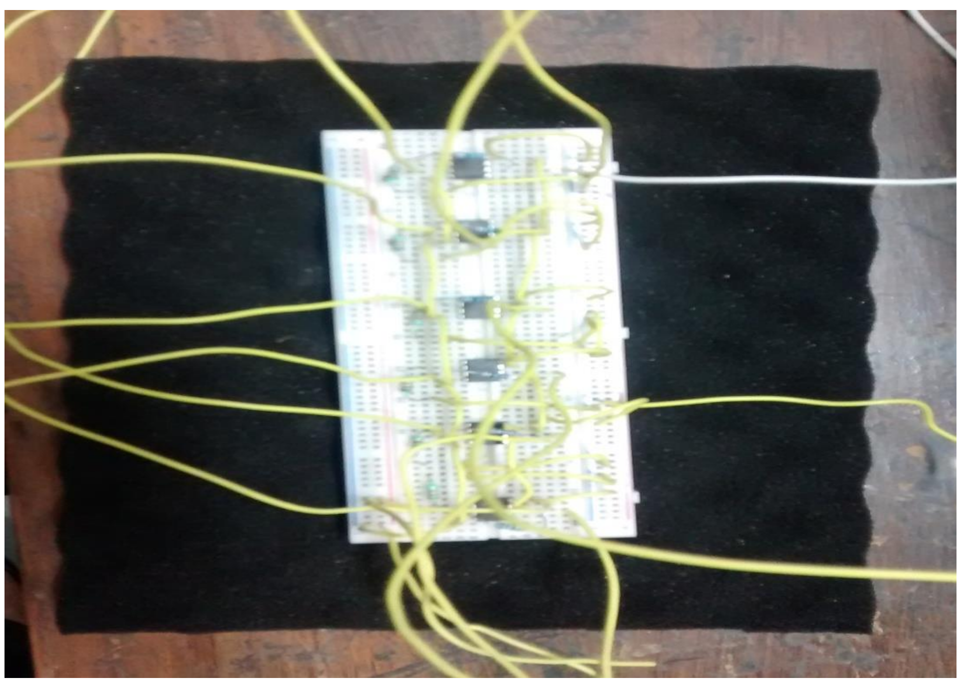


Fig. 7.6 Gate driver circuit hardware implementation

7.9 dSPACE (DS1104 CONTROL BOARD)

The DS1104 R&D Controller Board upgrades the PC to a development system for rapid control prototyping (RCP). The real-time hardware, based on a PowerPC microprocessor and its I/O interfaces make the board ideally suited for developing controllers in various fields, in both industry and academics. The DS1104 R&D Controller Board is a standard board that can be plugged into a PCI (Peripheral Component Interconnect) slot of a PC. The DS1104 is specifically designed for the development of high-speed multivariable digital controllers and real-time simulations in various fields. It is a complete real-time control system based on a 603 PowerPC floating point processor running at 250 MHz. For advanced I/O purposes, the board includes a slave-DSP subsystem based on the TMS320F240 DSP microcontroller. Interfacing of DS1104 & PC-MATLAB is done in order to ease the operation of control. The single phase current and voltage once sensed are fed to the ADC port of DS1104 by means of BNC cable. DS1104 interfaces with the MATLAB, where the control circuit is designed. The gate pulses are determined through the control circuitry. These gate pulses are then fed to the inverter through the Digital I/O connector port of DS1104 separated by the isolating circuit in order to prevent the gate from being shorted. The DS1104 contains two different types of analog/digital converters (ADCs) for the analog input channels:

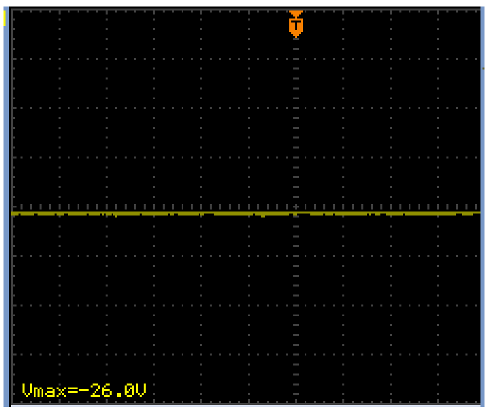
(i) One 16-bit ADC with four multiplexed input signals: the channels, ADCH1 ... ADCH4

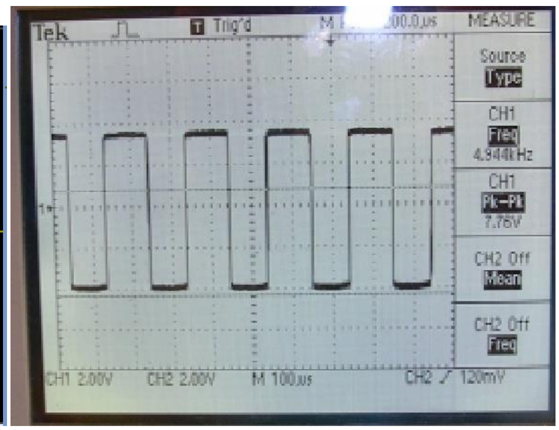
(ii) Four 12-bit parallel ADCs with one input signal each: the channels, ADCH5 ... ADCH8

The digital I/O connector (CP17) is a 37-pin, male Sub-D connector located on the front of the connector panel. The important thing to note is that the ADC input to the DS-1104 should be between ±10 V. In order to make this possible, the gain of current sensor and voltage sensor are accordingly set in the circuit. Fig 3.9 shows control desk screen of dSPACE. This is also known as CRO of dSPACE. In this CRO system parameters like supply voltage, current, firing pulses, etc. can be viewed both in waveform pattern as well as in magnitude.

7.10 HARDWARE RESULTS

The circuit is tested of a 20 kHZ switching frequency with a IGBT based single phase inverter. Solar PV module offers quite nonlinear VI characteristics and can supply limited voltage or current. Hence the MPPT is very much essential for optimizing the power output.This section discuss about the results obtained from the power converter with solar panel for a bright sunlight around 800 W/m^2 irradiance. Fig. 7.7 shows the PV output voltage with switching pulses of MOSFET switches.

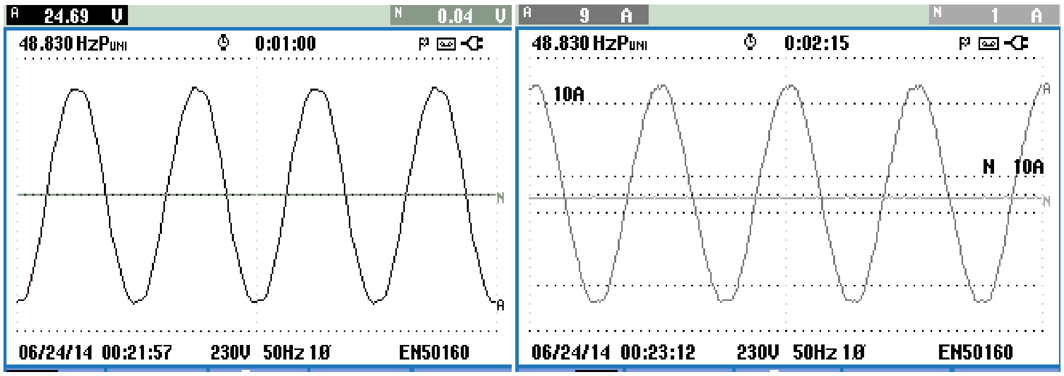




(a) (b)

Fig. 7.7(a)PV Output Voltage (V), (b) PWM signal for MOSFET switching

The above waveforms showing the inverter output voltage, current and THD in inverter current for R load are captured through the power analyzer and obtained results are as shown in the Fig. 7.7, 7.8 and 7.9 respectively.From Fig. 7.9 it is clearly seen that the THD of output current is 2.7 % and the values of output voltage isless than the expected value. This is due to losses across MOSFET switches, LC filter and in H bridge inverter switching and filtering.



(a) (b)

Fig. 7.8 Inverter Output for R Load (a) Voltage (V), (b) Current (A)

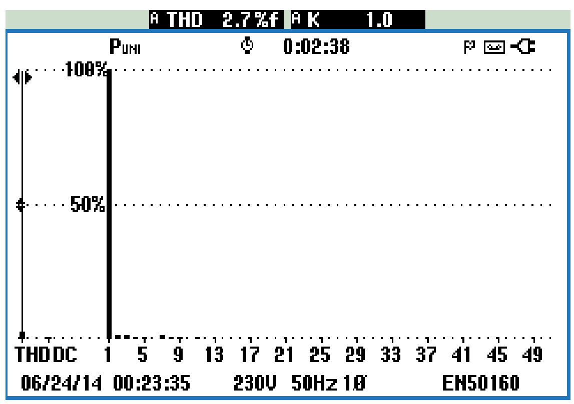


Fig. 7.9 THD of inverter output current

Fig. 7.10, 7.11 and 7.12 shows the inverter output voltage, current and THD in inverter current for RL load.The THD of output current is 6.8 %.

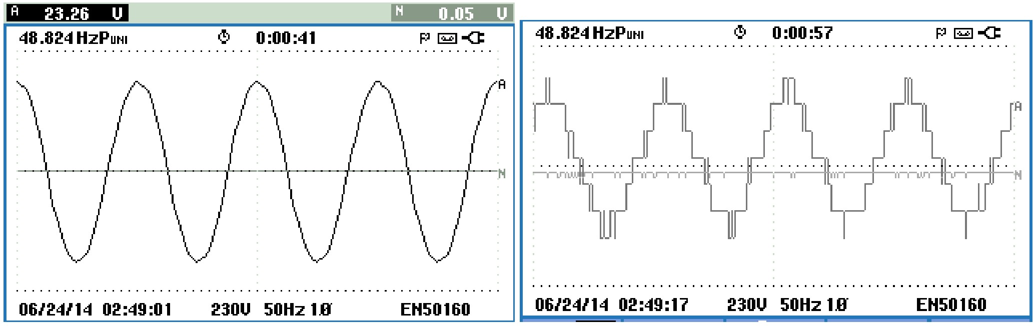


Fig. 7.10 Inverter Output for RL Load (a) Voltage (V), (b) Current (A)

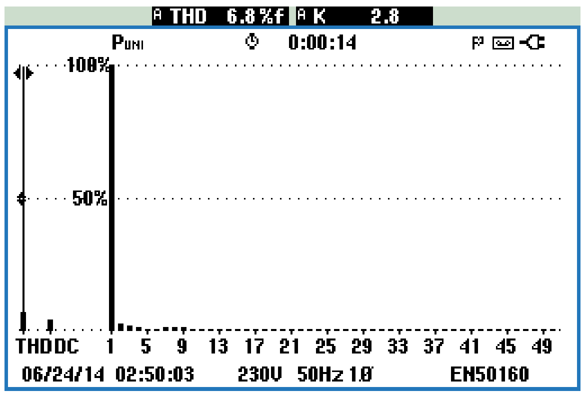


Fig. 7.11 THD of inverter output current

7.11 CONCLUSIONS

This chapter presents the hardware implementation of solar PV system with actual PV module, DC/DC boost converter and H bridge inverter. Complete analysis of system is shown for R and RL load with THD.

CHAPTER 8

RESULT & DISCUSSIONS

8.1 INTRODUCTION

This section presents a detailed discussion on the outcome of this research work. Firstly, the comparative analysis of various MPPT techniques is presented. Further various simulated control techniques of grid connected single phase solar PV system are compared on the basis of performance. Also results of three phase grid connected PV system are also discussed. A brief discussion on hardware results is also presented.

8.2 RESULT AND DISCUSSIONS

In this work, performance analysis of three MPPT techniques namely P & O, incremental conductance and constant voltage is carried out and presented. The performance is evaluated on different meteorological conditions like constant irradiance and temperature, varying irradiance and constant temperature, constant irradiance and varying temperature and finally at varying irradiance and temperature. The Summary of performance of three MPPT techniques is listed in Table 7.1.

In addition, battery charging characteristics is also evaluated on the basis of battery voltage and battery charging current. It is concluded that the performance of constant voltage technique is better as compared to others at constant irradiance and temperature whereas P & O approach is better at constant irradiance and varying temperature.

Table 7.1 Comparative analysis of P & O, Incremental Conductance and Constant Voltage MPPT techniques

Technique	Parameters			
	At constant irradiance and temperature	At varying irradiance and constant temperature	At constant irradiance and varying temperature	At varying irradiance and temperature
P & O	Large power ripples, large voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Large response time and Less stable	Large power ripples, Large voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Less response time and Less stable	Large power ripples but less than varying irradiance conditions, Large voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Less response time and Less stable	Large power ripples, Large voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Less response time and Less stable
Incremental Conductance	Less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Almost constant battery charging current, less response time, stable	Less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Large response time, Less stable	Less power ripples but more than varying irradiance conditions, Less voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Large response time, Less stable	Less power ripples but more than other three cases, Less voltage fluctuations, Constant charging voltage of battery, Oscillatory battery charging current, Large response time, Less stable
Constant Voltage	Very less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Almost constant battery charging current, Less response time, stable	Very less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Almost constant battery charging current, Less response time, Become unstable (for real time applications), Less accurate than constant conditions	Very less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Almost constant battery charging current, Less response time, Become unstable(for real time applications), Less accurate	Less power ripples, Less voltage fluctuations, Constant charging voltage of battery, Almost constant battery charging current, Less response time, Become unstable(for real time applications), Less accurate than constant conditions

However, the performance of incremental conductance approach is better as compared to other techniques at varying irradiance and constant temperature and varying solar irradiance and temperature. Therefore incremental conductance technique is better for evaluating the performance of PV system under meteorological parameters.

A single phase grid connected PV system has been designed and simulated in this work. Performance analysis is carried out for the two different control schemes namely synchronous reference based current controller and digital PI control. SRF based control of single phase grid connected system is found to be better in this case because it is simple and giving better results.

A three phase grid connected PV system has been designed and simulated with adaptive filter based grid synchronization technique. The capability of the designed control algorithm in extracting the positive sequence component has been tested and found to be very good as the results are satisfactory. The THD of source current is also very less only 3.75%.

A hardware implementation of the solar power converter with MPPT interfaced with actual solar array controlled using dSPACE is presented in this thesis. The voltage and current output are obtained for R and RL load. THD analysis of the output current is carried out and found within the limits. The proposed MPPT technique and control technique both are working properly with satisfactory results.

8.3CONCLUSION

This chapter presented a brief discussion for various outcomes of the research work carried out in this thesis.

CHAPTER 9

CONCLUSIONSAND FUTURE SCOPE

9.1INTRODUCTION

After discussing about the various aspects of this project 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.

9.2CONCLUSION

The objective of this project is divided into four parts; one is to design, modeling and simulationof standalone PV system with battery storage; second is to design, modeling and simulation of single phase grid connected PV system with different control techniques for grid synchronization, third objective is to design a three phase grid connected PV system with adaptive filter based grid synchronization approach and final is to implement hardware for single phase grid connected PV system. All the objectives have been met satisfactorily.

Performance analysis of three MPPT techniques namely P & O, incremental conductance and constant voltage is carried out and presented for solar photovoltaic (SPV) system. The performance is evaluated on different meteorological conditions like constant irradiance and temperature, varying irradiance and constant temperature, constant irradiance and varying temperature and finally at varying irradiance and temperature.

The simulated results for single phase grid connected PV system clearly shows the ability of theproposed control schemes to track MPP power fromthe PV module and grid synchronization. The MPPT used inthe control tracks the power very fast even under step change of insolation and the current controllerdelivers the power to the load with the grid synchronization functions. Single phaseSRF based technique is used which provides goodcontrol with cost effective solution. While the digital PI based current controller provides robust controlling method for the inverters as well as protects the PV system.The implemented schemes derive the advantage of simplicity and are capable of delivering undervarying irradiance conditions effectively.

Simulation analysis is presented in this thesis for three phase grid connected photovoltaic system with a control scheme.The proposed three phase adaptive notch filter based grid synchronization techniquegives high degree of insensitivity to disturbances, harmonics and other types of pollutions thatexist in the grid voltage and current signals. Moreover, the proposed control scheme is capable of decomposing three-phase quantities intosymmetrical components, observing the change in frequency and providing voltage regulation andreactive power control.

Practical hardware is implemented using dSPACE. The system is designed for low power ratings for practical validation of MPPT techniques and control algorithms. The system has been designed for20 kHz switching frequency due to the restriction from the optocoupler 6N136 and isolation circuits which are not able to respond at higher frequencies. The inverter is made of IGBT switches and has the limitation of maximum frequency up to 20 kHz and hence the switching frequency of the entire converter system has been limited to the same.

9.3FUTURE SCOPE

In this work the following objectives have been achieved successfully.

- Performance analysis of various MPPT techniques
- Single phase grid connected SPV system with control schemes
- Three phase grid connected SPV system with adaptive notch filter based grid synchronization technique

- A lab scale prototype development which consists of PV panel with DC/DC boost converter and a single phase inverter using dSPACE.

However, the present work can also be extended in future.

- Developed MPPT controller can be utilized for large scale grid connected systems.
- The hardware can be extended for grid connected 1 phase and 3 phase SPV systems.
- After developing the hardware, power quality analysis of grid connected PV systems can be carried out.
- Further, the SPV system can also be integrate with a DSTATCOM for complete reactive power compensation.

REFERENCES

[1] Jawaharlal Nehru National Solar Mission (JNNSM) report, Government of India, 2009, www.mnre.gov.in

[2] N Pandiarajan,R Ramaprabha and M Ranganath "Application of circuit model for photovoltaic energy conversion system" International Journal of Advanced Engineering Technology, 2(4): 118-127, 2011.

[3] N Pandiarajan and M Ranganath "Mathematical modeling of Photovoltaic module with Simulink, IEEE.pp. 258-263, 2011.

[4] Aissa Chouder "Modeling and simulation of a grid connected PV systems based on the evaluation of main PV module parameters" Sciverse Science-Direct, 2011.

[5] I H Altas and A M Sharaf "A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment" IEEE, Clean Electrical Power, International Conference on Clean Electrical Power (ICCEP '07), Ischia,Italy, June 14-16, 2007.

[6] K Ishaque, Zainal Salam and Hamed Tahri "Accurate MATLAB Simulink PV systems simulator based on a two-diode model" Journal of power electronics, 11(2), 2011.

[7] Samer Said, Ahmed Massoud, Mohieddine Benammar and Shehab Ahmed "A MATLAB/Simulink based photovoltaic array model employing Simpower system toolbox" Journal of Energy and Power Engineering 6, 1965-1975, 2012.

[8] 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.

[9] J. A. Gow and C. D.Manning “Development of a photovoltaic array model for use in power-electronics simulation studies” IEE Proceedings on Electric Power Applications, vol. 146, no. 2,pp. 193–200, 1999.

[10] Huan-Liang Tsai, Ci-Siang Tu, Yi-Jie Su “Development of Generalized Photovoltaic Model Using MATLAB/SIMULINK” Proceedings of the World Congress on Engineering and Computer Science WCECS, San Francisco, USA, 2008.

[11] D Amudhavalli , M Meyyappan, S Imaya. and V Preetha Kumari “ Interleaved soft switching boost converter with MPPT for photovoltaic power generation system”

[12] Yungtaek Jang, Senior Member and Milan M. Jovanovic “ New two inductor boost converter with auxiliary transformer” IEEE transactions on power electronics, vol. 19, no. 1, January 2004

[13] T.Shanthi and N.Ammasai Gounden “Power electronics interface for grid connected PV array using boost converter and line-commutated inverter with MPPT” International Conference on Intelligent and Advanced Systems 2007.

[14] Ahmad H. El Khateb, Nasrudin Abd Rahim, and Jeyraj Selvaraj “ Cuk – buck converter for standalone photovoltaic systems” Journal of Clean Energy Technologies, Vol. 1, No. 1, January 2013.

[15] Hairul Nissah Zainudin and Saad Mekhilef “ Comparison study of maximum power point tracker techniques for PV systems” Proceedings of the 14th International Middle East Power Systems Conference (MEPCON’10), Cairo University, Egypt, December 19-21, 2010.

[16] C P Paul, Wei Dar Chen and Chih-Kuo Chang “ Maximum power tracking of a generic photovoltaic system via a fuzzy controller and a two stage DC/DC converter” Microsyst Technol , 18:1267–1281, 2012.

[17] M. Abdulkadir, A. S. Samosir, Member and A. H. M. Yatim " Modeling and simulation of maximum power point tracking of photovoltaic system in Simulink model" IEEE International Conference on Power and Energy (PECon), Kota Kinabalu Sabah, Malaysia, 2012.

[18] Mostafa Mosal, Haitham Abu Rubl, Mahrous E, Ahmed and Jose Rodriguez " Modified MPPT with using model predictive control for multilevel boost converter" IEEE, pp 5080-5085, 2012.

[19] F Z Hamidon, P D Abd Aziz and N H Mohd Yunus "Photovoltaic array modeling with P & O MPPT algorithms in MATLAB" 2010.

[20] Ali F Murtaza, Hadeed Ahmed Sher, Chiaberge M, Boero D, De Giuseppe M1 and Khaled E Addoweesh " A novel hybrid MPPT technique for solar PV applications using perturb and observe and fractional open circuit voltage techniques" 2010.

[21] Ali Nasr Allah Ali, Mohamed H. Saied, M. Z. Mostafa and T. M. Abdel Moneim"A survey of maximum PPT techniques of PV systems" 2011.

[22] Seok Il Go, Seon Ju Ahn, Joon Ho Choi, Won Wook Jung, Sang Yun Yun and Il Keun Song "Simulation and analysis of existing MPPT control methods in a PV generation system" Journal of International Council on Electrical Engineering Vol. 1, No. 4, pp. 446 - 451, 2011.

[23] A R Reisi, Moradi M H and S Jamsab, "Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review" Renewable and Sustainable Energy Reviews 19, 433-443, 2013.

[24] R Faranda, S Leva and V Maugeri. "MPPT techniques for PV systems: energetic and cost comparison" Proceedings of IEEE PES GM 2008, July 2008.

[25] M A S Masoum, H Dehbonei and E F Fuchs "Theoretical and experimental analysis of photovoltaic systems with voltage and current based maximum power-point tracking" IEEE Transactions on Energy Converters, 7(4), 514-522, 2002.

[26] K H Hussein, I Muta, T Hoshino and M Osakada. “Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions” IEEE proceedings Generation, Transmission and Distribution, 142, 59-64, 1995.

[27] H Desai, P Patel and H K Patel. “Maximum power point algorithm in PV generation an overview” IEEE Proceedings of power electronics and drive systems. 2007.

[28] D Hohm and M Ropp “Comparative study of Maximum Power Point Tracking Algorithms” Progr. Photovoltaics. 2003; 11, 47-62.

[29] Y C Kuo, T J Liang and J F Chen “Novel maximum-power point tracking controller for photovoltaic energy conversion system” IEEE Transactions Industrial Electronics 48 (3), 594–601, 2001.

[30] T Esram and P L Chapman “Comparison of photovoltaic array maximum power point tracking techniques” IEEE Transaction Energy Conversion, 22 (2), 439–449, 2007.

[31] H Patel and V Agarwal “Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions” Industrial Electronics, IEEE Transactions 55 (4), 1689-1698, 2008.

[32] V Salas, E Olias, A Barrado and A L Zaro. “Review of the maximum power point tracking algorithms for stand-alone photovoltaic system” Solar Energy Materials & Solar cells. 90, 1555-78, 2006.

[33] K Kobayashi, I Takano and Y Sawada. “A study on a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions” IEEE Power Engineering Society General Meeting, 2612-2617, 2003.

[34] A B Bahgat, N H Helwab, G E Ahmadb and E T Shenawyb “Maximum power point tracking controller for PV systems using neural networks” Renewable Energy. 30, 1257–68, 2005.

[35] G J Yu, M W Jung , J Song, I S Cha and I H Hwang “Maximum power point tracking with temperature compensation of photovoltaic for air conditioning system with fuzzy controller” In Proceedings IEEE Photovoltaic Spec. Conf. 1429–1432, 1996.

[36] M G Simoes, N N Franceschetti and M Friedhofer “A fuzzy logic based photovoltaic peak power tracking control” In Proceedings IEEE Int. Symp. Ind. Electron, 300–355, 1998.

[37] C B Salah and M Ouali “Comparison of fuzzy logic and neural network in maximum power point tracker for PV systems” Electric Power Systems Research. 81, 43–50, 2011.

[38] C P Ragasudha, H Algazar, A L Monier, H A El-halim and M E K Salem “Maximum power point tracking using fuzzy logic control” Electrical Power and Energy Systems. 392, 1-8, 2012.

[39] A Messaia, A Mellitb, A M Pavanc, A Guessoumd and H Mekkia “FPGA-based implementation of a fuzzy controller (MPPT) for photovoltaic module” Energy Conversion and Management. 52 (7), 2695–2704, 2011.

[40] T Hiyama, S Kouzuma and T Imakubo. “Identification of optimal operating point of PV modules using neural network for real time maximum power tracking control” IEEE Transactions on Energy Conversion. 10 (2), 360–7, 1995.

[41] T Hiyama and K Kitabayashi “Neural network based estimation of maximum power generation from PV module using environmental information” IEEE Transactions on Energy Conversion. 12, 241–7, 1997.

[42] F Giraud and Z M Salameh “Analysis of the effects of a passing cloud on a grid-interactive photovoltaic system with battery storage using neural networks” IEEE Transactions on Energy Conversion. 14(4), 1572–7, 1999.

[43] Al moudi A and L Zhang "Application of radial basis function networks for solar-array modeling and maximum power point prediction" IEE Proceedings. 147 (5), 310–316, 2000.

[44] C Y Won, D H Kim, S C Kim, W S Kim and H S Kim "A new maximum power point tracker of photovoltaic arrays using fuzzy controller" In Proceedings of 25th Annu. IEEE Power Electronics Spec.Conf. 396–403, 1994.

[45] T Senjyu and K Uezato "Maximum power point tracker using fuzzy control for photovoltaic arrays" Proceedings of IEEE Int. Conf. Ind. Technol. 143–147, 1994.

[46] M G Villalva, J R Gazoli and E R Filho "Comprehensive approach to modeling & Simulation of Photovoltaic Arrays" IEEE Transactions on Power Electronics, 24 (5), 1198 – 1208, 2009.

[47] O Rivera. "Maximum Power Point Tracking using the Optimal Duty ratio for DC-DC Convertors and Load Matching in Photovoltaic Applications" IEEE. 987-991, 2008.

[48] G Adamidis, P Bakas and A Balouktsis "Photovoltaic System MPPTracker Implementation using DSP engine and buck-boost DC-C converter".

[49] J H R Enslin and D B Snyman. "Combined low-cost, high-efficient inverter, peak power tracker and regulator for PV applications" IEEE Transactions on Power Electronics 1991; 6 (1), 73-82.

[50] E Koutroulis and K Kalaitzakis "Novel battery charging regulation system for photovoltaic applications" Proceedings of Institute of Electrical Engineering.-Electrical Power Applications 151 (2), 191-197, 2004.

[51] M H Rashid "Introduction to Buck-Boost converter design" Third edition, Pearson education.

[52] J Vieira and A Mota "Maximum Power Point Tracker Applied in Batteries Charging with PV Panels" IEEE International Symposium on Industrial Electronics, USIE, 1, 202-206, 2008.

[53] Z Salameh, F Dagher and W Lynch “Step-down maximum power point tracker for photovoltaic systems” Solar Energy, 46 (5), 270-282, 1991.

[54] P I Muoks, M E Hawel, A Gargoomed and M Negnevitsky“Modeling and simulation and hardware implementation of a PV power plant in a distributed energy generation system” IEEE, 2013.

[55] S B Kjaer, J K Pedersen and F Blaabjerg “A review of single phase grid-connected inverters for photovoltaic modules,” IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1292-1306,Sep/Oct. 2005.

[56] Q Li and P Wolfs, “A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations,” IEEE Transactions on Power Electronics, vol. 23,no. 3, pp. 1320-1333, May. 2008.

[57] Fritz Schimpf and Lars E. Norum “ Grid connected converter for photovoltaic state of art, ideas for improvement of transformerless inverters” Nordic Workshop on Power and Industrial Electronics, June 9-11, 2008.

[58] Luigi G Junior, Moacyr A G de Brito, Leonardo P Sampaio and Carlos A Canesin “ Evaluation of integrated inverter topologies for low power PV systems” IEEE, 2011.

[59] R Wai and W Wang, “Grid-connected photovoltaic generation system,” IEEE Transactions on Circuits and Systems-I, vol. 55, no. 3,pp. 953-963, Apr. 2008.

[60] Shuai Jiang, Dong Cao, and Fang Zheng Peng, “Grid-Connected Boost-Half-Bridge Photovoltaic Microinverter System Using Repetitive Current Control and Maximum Power Point Tracking”, in IEEE transactions on power electronics, VOL. 27, no. 11, november 2012.

[61] Robert H Lasseter, “Microgrids and Distributed Generation”Journal of Energy Engineering, American Society of Civil Engineers, September 2007.

[62] D C Martins and R Demonti, "Grid connected PV system using two energy processing stages," in Proceedings of IEEE Photovoltaic Specialists Conference, pp. 1649-1652, 2002.

[63] N Kasa, T Iida and L Chen, "Flyback inverter controlled by sensorless current MPPT for photovoltaic power system," IEEE Trans. Ind. Electron., vol. 52, no. 4, pp. 1145–1152, Aug. 2005.

[64] S B Kjaer and F Blaabjerg, "Design optimization of a single phase inverter for photovoltaic applications," in Proc. IEEE PESC, pp. 1183–1190, 2003.

[65] H Li, F Z Peng and J S Lawler, "Modeling, simulation, and experimental verification of soft-switched bi-directional dc-dc converters," in Proceedings of. IEEE APEC, pp. 736–742, 2001.

[66] F Z Peng, H Li, G Su and J S Lawler, "A new ZVS bidirectionalDC– DC converter for fuel cell and battery application," IEEE Transactions on Power Electronics, vol. 19, no. 1, pp. 54–65, Jan. 2004.

[67] D Liu and H Li, "A ZVS bi-directional DC–DC converter for multiple energy storage elements," IEEE Transactions on Power Electronics, vol.21, no. 5, pp. 1513–1517, Sep. 2006.

[68] E Koutroulis, K Kalaitzakis and N C Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system," IEEE Transactions on Power Electronics, vol. 16, no. 21, pp.46–54, Jan. 2001.

[69] A K Abdelsalam, A M Massoud, S Ahmed and P Enjeti, "High performance adaptive perturb and observe MPPT technique for photovoltaic-based microgrids" IEEE Transactions on Power. Electronics, vol.26, no. 4, pp. 1010–1021, Apr. 2011.

[70] Y C Kuo, T J Liang, and J F Chen, "Novel maximum-power point tracking controller for photovoltaic energy conversion system,"IEEE Trans. Ind. Electron., vol. 48, no. 3, pp. 594–601, Jun. 2001.

[71] Y H Lim and D C Hamill, “Simple maximum power point tracker for photovoltaic arrays,” Electron. Lett., vol. 36, pp. 997–999, May 2000.

[72] T Esram and P L Chapman, “Comparison of photovoltaic array maximum power point tracking techniques,” IEEE Trans.Energy Conv., vol. 22, no. 2, pp. 439–449, Jun. 2007.

[73] S Jain and V Agarwal, “Comparison of the performance of maximum power point tracking schemes applied to single-stage grid connected photovoltaic systems,” IET Electr. Power Appl., vol. 1, no.5, pp. 753–762, Sep. 2007.

[74] B A Francis and W M Wonham, “The internal model principle for linear multivariable regulators,” Appl. Math. Opt. vol. 2, pp. 170-194, 1975.

[75] E Twining and D G Holmes, “Grid current regulation of a three phase voltage source inverter with an LCL input filter,” IEEE Transactions on Power. Electronincs, vol. 18, no. 3, pp. 888–895, May. 2003.

[76] Yu Kang Lo, Jin Yuan Lin and Tin Yuan Wu “Grid connection technique for a photovoltaic system with power factor correction” IEEE PEDS, 2005.

[77] H Toodeji, N Farokhnia and G H Riahy “Integration of PV module and STATCOM to extract maximum power from PV” 2009.

[78] A Papavasilou, S A Papathanassiou, S N Manias and G Demetriadis “ Current control of a voltage source inverter connected to grid via LCL filter” 2004.

[79] D Amorndechaphon, S Premrudeepreechacharn and K Higuchi “Small grid connected PV system with lossless passive soft switching technique” Fukuoka International Congress Center, Japan, 2009.

[80] Yongheng Yang and Frede Blaabjerg “ Synchronization in single phase grid connected photovoltaic systems under grid faults” 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) 2012.

[81] Linda Hassaine, Emilio Olías, Jesús Quintero and Andrés Barrado " Power control for grid connected applications based on the phase shifting of the inverter output voltage with respect to the grid voltage" Electrical Power and Energy Systems 57, pp 250–260, 2014.

[82] J Selvaraj, N A Rahim and C Krismadinata "Digital PI control for grid connected PV inverters" IEEE, 2008.

[83] Huijuan Li, Member, Yan Xu, Senior Member and Sarina Adhikari "Real and reactive power control of a three phase single stage PV system and PV voltage stability" IEEE, 2012.

[84] David M Aletr "Thermoelectric cooler control using TMS320F2812DSP and a DRV592 power amplifier" Texas Instruments Application Report.

[85] Shuai Jiang, Dong Cao, Fang Z. Peng and Yuan Li " Grid connected Boost half bridge photovoltaic micro inverter system using repetitive current control and maximum power point tracking, IEEE, 2012.

[86] G Shen, D Xu, L, Cao and X Zhu, "An improved control strategy for grid-connected voltage source inverters with an LCL filter," IEEE Trans. Power Electron., vol. 23, no. 4, pp. 1899–1906, Jul. 2008.

[87] M Liserre, F Blaabjerg and S Hansen, "Design and control of an LCL-filter-based three-phase cctive rectifier," IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1281-1291, Sep/Oct. 2005.

[88] J Dannehl, M Liserre and F W Fuchs, "Filter-based active damping of voltage source converters with LCL filter," IEEE Trans. Ind.Electron., vol. 58, no. 8, pp. 3623–3633, Aug. 2011.

[89] Jiri Lettl, Jan Bauer, and Libor Linhart " Comparison of different filters types for grid connected inveretrs" PIERS Proceedings, Marrakesh, MOROCCO, pp 1426-1429, 2011.

[90] Issa Battarsha, Power Electronics Circuits, John Wiley and Sons Inc, 2004.

[91] Marian K. Kazimierczuk, Pulse-width Modulated DC–DC Power Converters, A John Wiley and Sons, Ltd, Publication, 2009.

[92] Kyoung Jun Lee, Jong Pil Lee, Dongsul Shin, Dong-Wook Yoo and Hee-Je Kim "A Novel Grid Synchronization PLL Method Based on Adaptive Low-Pass Notch Filter for Grid-Connected PCS" IEEE transactions on industrial electronics, vol. 61, no. 1, pp 292-301, 2014.

[93] Hoon Young Jung, Young Hyok Ji, Chung Yuen Won, Doo-Young Song, Jin Wook Kim "Improved Grid-synchronization Technique based on Adaptive Notch Filter" International Power Electronics Conference, pp 1494-1498, 2010.

[94] Davood Yazdani, Alireza Bakhshai and Praveen Jain "Adaptive Notch Filtering Based Grid Synchronization Techniques for Converter Interfaced Distributed Generation Systems" IEEE, pp 3963-3969, 2009.

[95] Davood Yazdani, Alireza Bakhshai, Géza Joós and Mohsen Mojiri "A Real-Time Extraction of Harmonic and Reactive Current in a Nonlinear Load for Grid-Connected Converters" IEEE transactions on industrial electronics, vol. 56, no. 6, june 2009.

[96] Arun Verma, Bhim Singh, D T Sahani, "Grid Interfaced Photovoltaic power generating system with Power Quality Improvement at AC mains," IEEE ICSET, 2012, Nepal.

[97] Farid Katiraei, Reza Iravani, Nikos Hatziargyriou and Aris Dimeas "Microgrid management Control and operation aspect of microgrids," IEEE Power & Energy Magazine, May/June 2008.

[98] S A Azmi, G P Adam, Khaled H Ahmed, Stephen J Finney, Barry W Williams, "Grid Interfacing of Multimegawatts Photovoltaic Inverters," IEEE Transaction on Power Electronics, vol.28, no.6, june2013.

[99] Arun Verma, Bhim Singh and D T Sahani, "Power Balanced theory based Grid Interfaced Photovoltaic power generating system with Power Quality Improvement at AC mains," in Proc. for the IEEEInternational conference on Power Electronics, Drives and Energy systems, 16-19 Dec, 2012.

[100] Ned Mohan, Tore M Undeland and William P Robbins, "Power electronics converters, applications, and design", Wiley India Press Pvt. Ltd. Third Edition, Reprint 2009

[101] S K Khadem, M Basu and M F Conlon "Power quality in grid connected renewable energy systems: Role of custom power devices" International conference on renewable energies and power quality (ICREPQ'10) Granada (Spain), March 2010.

[102] Masoud Farhoodnea, Azah Mohamed, Hussain Shareef and Hadi Zayandehroodi "Power quality analysis of grid connected photovoltaic system in distribution networks" Przegląd Elektrotechniczny, 2013.

LIST OF PUBLICATIONS

- M. Rizwan, Priyanka Chaudhary and Tausif Ahmad, "Performance Analysis Of Maximum Power Point Tracking Techniques For Photovoltaic Systems" Accepted in Advance Science Letters, USA (ISSN: 1936-6612) Impact Factor- 1.253.
- Priyanka Chaudhary, M. Rizwan and Tausif Ahmad, "Matlab/Simulink Based Modeling and Simulation of Photovoltaic Array" International Conference on Advance Research and Innovation. 2014.