DESIGN AND DEVELOPMENT OF ROOFTOP SOLAR SYSTEM

A DISSERTATION

Submitted In Partial Fulfillment Of The

Requirements for the Award of Degree

Of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Electric Drives and Power Electronics)

by

PRAKHAR PATIDAR

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ROORKEE – 247667

MAY 2016

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this report entitled "**Design and Development of Rooftop Solar System**" in partial fulfilment of requirement for the award of degree of Master of technology in Electrical Engineering with specialization in Electric Drives & Power Electronics, and submitted in the Department of electrical Engineering of indian institute of technology Roorkee, India, is an authentic record of my own work carried out during the period from June 2015 to May 2016, under the supervision of Dr. S.P. Singh, Professor, Department of Electrical Engineering, of indian institute of technology Roorkee, India.

The matter embodied in this report has not been submitted by me or by anyone for the award of any other degree of this or any other Institute/ University.

Date: 23rd May, 2015 **PRAKHAR PATIDAR**

Place: Roorkee **E. No. - 14527016**

CERTIFICATE

This is to certify that the statement made by the candidate is correct to the best of knowledge and belief. He has made a good efforts to compile the information and data form the past researchers.

Date :

Dr. S.P. SINGH

Professor

Department of Electrical Engineering

Indian Institute of Technology, Roorkee

Roorkee – 247667

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Dated: 23rd May, 2016 **PRAKHAR PATIDAR**

Place: Roorkee **E. No. 14527002**

ABSTRACT

Solar energy is the most emerging renewable energy. Applications of solar energy are increasing for both gird connected and standalone system. Large power grid connection solar systems are developed by giant power companies. But standalone system can be established by normal person at available places of roof of house, office, hospitals, schools etc. That's why they are becoming much popular than others.

At an area of 1000 sq. feet, 8 kWp solar system can be installed. Before install rooftop optimal rooftop area calculation is required. Once installed rooftop roof cannot be used for most of other purposes. In this report standalone as well as gird connected solar system are designed and simulated in MATALB. MPPT being the essential part of solar photovoltaic system is simulated using Incremental conductance plus integral regulator technique in MATLAB environment in chapter 4. For grid connection Vdc control and feed forward control is used. Results are shown in chapter 8. A boost DC-DC converter and inverter are employed to achieve this goal. To implement the system in real time hardware FPGA controller is used. FPGA uses HDL (Hardware Description language) to describe the system.

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List of Symbols and Constants

q = electron charge, 1.602e-19C

k = Boltzmann constant, 1.38e-23 J/K

a = diode ideality factor, 1.3

R_s = equivalent series resistance of solar cell,

R_{sh} = equivalent shunt resistance of solar cell,

E_g = Band gap energy, 1.12eV

T = cell temperature in Kelvin,

T_n = Nominal cell temperature,

I_{scn} = short circuit current of cell,

V_{ocn} = open circuit voltage of cell,

K_i = temperature current coefficient,

G = Irradiation Wh/m^2,

G_n = Nominal irradiation,

Ns = Number of series connected cell,

Np = Number of parallel connected module,

MPPT = maximum power point tracking,

D = duty ratio

V_{in} = Input voltage,

V_o = Output voltage,

D = Duty ratio,

f = switching frequency,

P = Converter power level,

R = load resistance.

L, C = inductance and conductance.

CONTENTS

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

The human life we see today around us is a result of its creative thinking process, desire to make life more comfortable and time to time revolutions to meet the various increasing demands. As time advancing the population of the human on earth is also increasing and demanding more energy. This energy is required in many form but ultimately can be converted in suitable form, from electrical energy. Electrical energy is generated from fossil fuels like coal, gas and oil but these are not going to last longer. Then we came to the renewable energy sources like solar, wind, hydro etc. which will be available till the existence of earth. Solar energy clean, quiet and available for free, is a good solution of the increasing power demand. Energy from sun can be extracted as either from solar thermal in heat form or from solar photovoltaic in electric from. As electric energy can be conditioned in desirable from with advance power electronic converters and modules plus electric energy is easy to transfer and conversion in other form of energies, energy extracted form solar photovoltaic is more useful. Solar thermal energy is also used in concentrated solar plant where solar thermal energy is used to heat up the water in vapor form and later sent to turbine generator set to generate the electrical energy.

India, due to its geographical position near around equator, receives abundant amount of radiation and has tremendous potential to emerge as one of the leaders in solar power sector. Most part of the India's land receives around 4-7 kWh/m^2/day. According to the Government of India's policy a target to generate 20,000 MW of grid connected solar power is set by 2022. For this Jawaharlal Nehru National Solar Mission (JNNSM) was launched on dated 11th January, 2010 by the Prime Minister of India. Installing solar system requires free area depending upon the installing capacity. A lot of research is currently going on solar. Every country is trying to maximize this free and abundant energy source to reduce their dependency on conventional energy sources. China, Germany, Japan and U.S. are top four solar energy producing countries. India is on tenth position in 2015.

Solar photovoltaic is the best substitute for the electrical energy in demand. Form small power rating of 24 watts to several MW plants are currently using this method. Size of plant increases with power rating. Large plant of kW ranges requires large area and are necessarily grid connected. Nowadays trend is going to install solar plants on the vacant roofs of buildings. Form here the concept of rooftop solar system emerged.

1.2 TYPES OF ROOFTOP SOLAR SYSTEM

Roof top installation of the solar system is the best choice of any solar system. Some key points strengthening the above statements are as follows:-

- They can be installed easily and quickly from other type of renewable energy structure present.
- Uses the free space available on the roof of the houses, school, governmental buildings, parking canopy etc. Thus saving in land requirement and costs.
- Saving in development of new mounting structure.
- Can be grid connected or standalone. Both provide good financial return.
- Reduced electricity bills of grid supply.
- Have long life of 25 year with less maintenance.

Generally houses and buildings are connected to the grid for electrical energy and depends upon the grid energy availability. Rooftop solar system on such sites can be of two types

1. Standalone rooftop solar system
2. Grid-connected rooftop solar system

1.2.1 Standalone Rooftop Solar System

Block diagram shown below outlines various components required for standalone rooftop solar system and described in brief.

PV array converts the solar radiation directly into electric energy. Power produced depends upon the incident radiation and temperature at a time. The characteristic of the PV source also depends on the load. At a particular load it produces maximum power. To meet the source and load impedance to transfer maximum power **MPPT** (Maximum Power Point Tracker) is used, which change the duty ratio of a **DC-DC** converter accordingly.

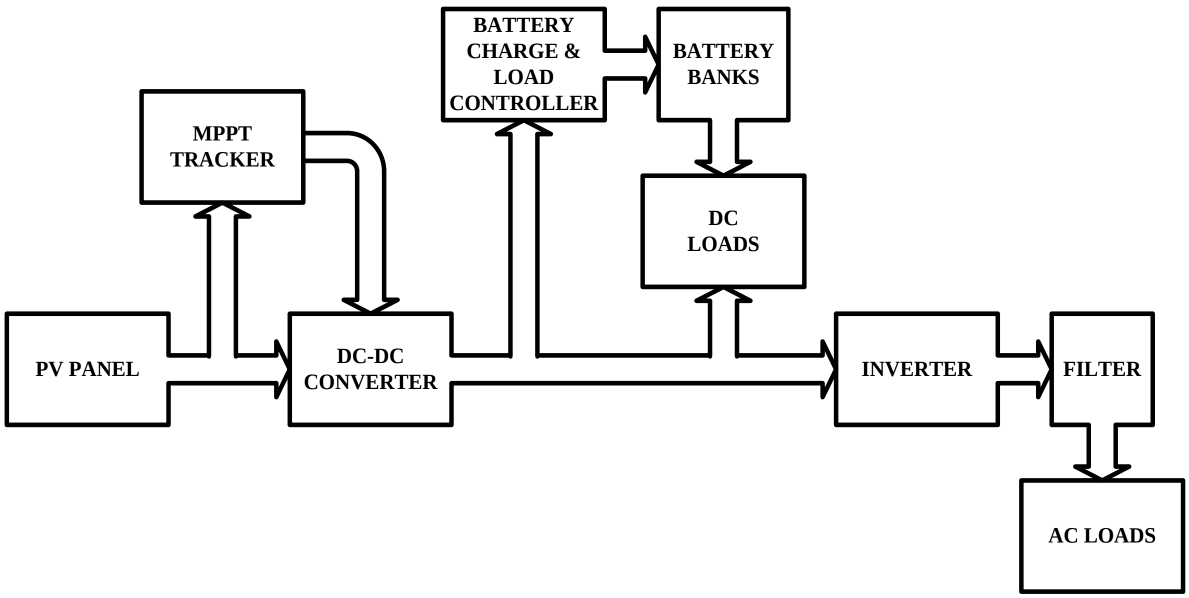

Fig. 1.1 Block diagram of typical standalone system

One of the important part of the standalone systems are **Battery Banks**. They are necessary to supply to load when there is no sun i.e. during cloudy weather and nights. **Battery charge controller** prevent the overcharging and over discharging of the batteries.

DC loads is supplied directly form the PV array output. A DC-DC converter can be used to match the load voltage demand.

An off-grid inverter is used to convert dc to ac supply with close loop control to meet the load requirement of 230V, 50 Hz. Filter is used to filter out component other than fundamental frequency. All these parts are described later in detail in successive chapters.

Total power generated from solar is equal to power supplied to batteries, DC load and AC load.

1.2.2 Grid connected rooftop solar system

They are basically hybrid system which uses both solar supply and grid supply. Use of batteries is generally avoided as grid supply is available. But for the areas where grid supply is not always available battery backup can be used.

The concept of **net metering** is introduced in rooftop grid connected systems. PV panels are installed based on the available roof areas. The output of panels is connected to the power conditioned unit of an inverter which converts the DC into AC. The output of the inverter is connected to the distribution board of the building to utilize the power. The inverter is synchronized with the grid. Control scheme is such that load first used the power coming from solar. If load is more than installed capacity of the solar system then it takes power form grid and if load is less than the solar power if feed the supply to the grid. Net energy meter is used in such cases which calculate the net flow of energy in a particular direction. The used has to pay only for the net grid supply used and sometimes bill is negative which means the utility pays to the consumer.

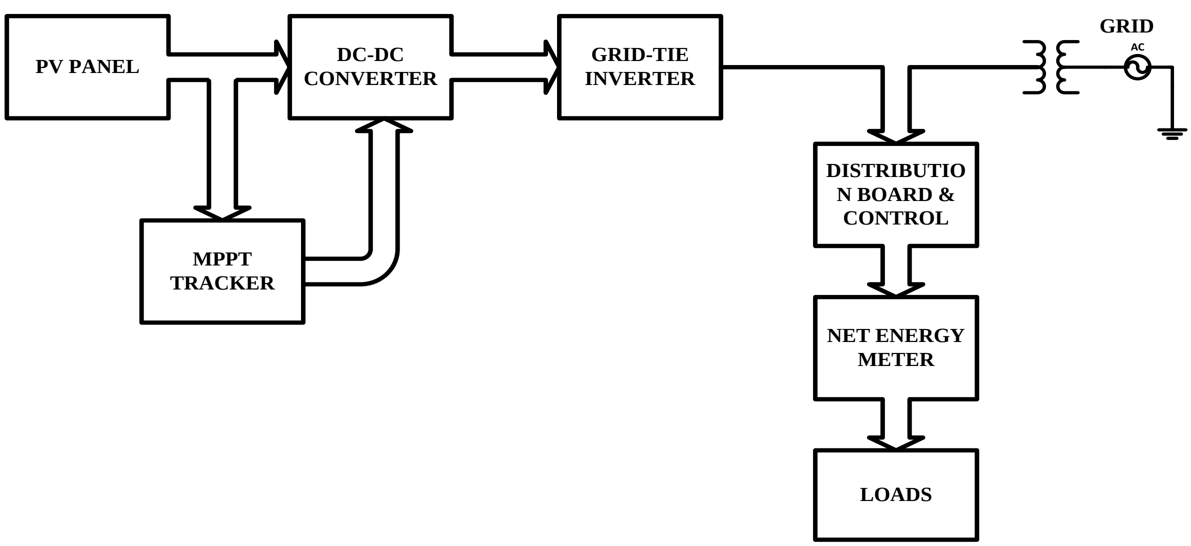

Fig. 1.2 Block Diagram of Grid Connected Rooftop solar system

There are various single stage converter which converts directly form panel DC output to grid voltage and frequency with MPPT algorithm and real and reactive power control.

1.3 Literature Review

Jazayeri, Moein, Sener Uysal, and Kian Jazayeri [1] says the elementary part of the complete system are solar modules. They can be simulated in MATLAB using the equation described a solar cell. They have used one diode model of solar cell. Parameters are taken from manufacturer’s datasheets. Series and parallel resistances are calculated from equation based on mathematical maximum power to panel’s maximum power ratings. These are highly nonlinear equations and MATLAB is a powerful and extensive tool for solving the equations and plotting the results.

Designing of rooftop solar system includes sizing of solar panels and battery bank. Authors of [25] have done a detailed study of sizing the solar system. DC and AC load of a moderate house is calculated first including wire efficiency in worksheet 1. In worksheet 2 they have calculated tilt angle of solar panels. Worksheet 3 detailed about battery bank calculation for 70% depth of discharge and 6 days of autonomy. Worksheet 4 concludes about series and parallel connection of solar module.

Jiang, Yuncong, Jaber Qahouq and Issa Batarseh in their paper "Improved solar PV cell MATALB simulation model and comparison" [3] described the improved cell equation using better dependency of photon current on radiation and cell voltage on temperature. Load variation effects are also considered in designing.

To establish a solar standalone system for a particular location one need to look the solar richness of site. For this some online calculators for irradiation and tilt angle are provided by www.solarelectricityhandbook.com [6]. Solar irradiation available at a particular site on the earth can be calculated using the location coordinates i.e. latitudes and longitudes. Tilt angle of the panels varies throughout the year to get maximum of radiation. Month wise tilt angel can be tabulated using another calculator mentioned on the same site.

To get sun path chart throughout the year for a particular place anywhere on earth, university of Oregon, USA has their solar radiation monitoring laboratory and they provided an online calculator for this [7]. Tracking sun path is also another key factor in determining the tilt angle of the panels.

Abdulkadir, M., et al. "A new approach of modelling, simulation of MPPT for photovoltaic system in Simulink model." Used incremental conductance plus integral regulator to track the MPPT of solar system [8]. He claimed that if properly tuned integral controller is used this algorithm can track MPPT vary fast. Use of integral controller also reduces the steady state error or ripples around the MPPT.

Al-Diab, Ahmad, and Constantinos Sourkounis in their paper "Variable step size P&O MPPT algorithm for PV systems" [9] modified the basis P&O algorithm. In conventional P&O step size is constant that makes the algorithm slow converging to MPP. In this paper variable step size is used. When operating point is far from MPP step size is large and when reaches near to MPP step size reduces.

A comparison between bipolar and unipolar PWM inverters topologies is given reference [22]. THD analysis of output voltage waveform is shown as a comparative study. It can be concluded form the paper that unipolar modulation scheme has reduced size of filters as dominant order harmonic in this are almost double that of bipolar modulation scheme.

Filter designing is described in Continuous Time Filters (P. Allen) – Chapter1 [23]. Both active and passive filters are dealt in detail. Transfer function of the filter can be calculated using input and output voltage equation. To design a low pass filter root of characteristic equation of the transfer function are calculated. To possess a stable system real part of pole of transfer function should lie in left of vertical axis. Filter is designed the by choosing value of quality factor to 0.707.

1.4 ORGANIZATION OF THESIS

This thesis is organized in a step by step manner to present the related work.

Chapter 1 includes the introduction and types of rooftop solar power system. It describes the brief description about each component of standalone and grid-tied solar system. Literature review also describes views of various transactions and conference papers.

Chapter 2 consists detailed study of designing the solar system. Various online calculator are used to determine the optimal tilt angle and irradiation of a particular site location. A table calculates the load on a small house and to meet this load requirement solar array size is calculated. To provide an autonomy of 3 days no. of lead-acid batteries are designed.

Thus the system can work continuously 3 days with no sun in the sky if batteries are fully charged.

Chapter 3 explains the very basics of photovoltaic energy conversion. It describes in detail how solar radiation is converted into electrical energy. A mathematical model of solar cell and its governing equations are described basis on which solar cell can be modelled in MATLAB. MPPT is essential part of the system. A number of methods are available to achieve this goal. Some of them are described in brief and incremental conductance algorithm with integral regulator is discussed in detail.

Chapter 4 presents some additional study about designing the controller which is very important for close loop system. System using power electronics converters are closed loop. Averaging state space model is built to design the controller. MATALB scripts and pidtuner tool is used and described.

Chapter 5 accelerates the work towards the design of battery charge controller, DC-DC converters, inverter, and low pass LC filter. Unipolar modulation method is used as a control scheme of the inverter.

Chapter 6 simulates all the above mentioned methods and circuits to develop a standalone solar system. MATALB is used as a simulation tool. Various results are shown and comparison is done.

Chapter 7 leads towards the real time practice of the title rooftop solar system. To develop the complete hardware system a number of small components and controller are required. This chapter shows various hardware figure and detailed component diagram. Then hardware results are shown.

Chapter 8 suggests future scope and better implementation methodology.

1.5 CONCLUSION

Rooftop solar systems are one of the best utilization of the resources because no need to invest on area. To maximize the efficiency a huge number of topologies are developed. Along with MPPT single stage conversion is more popular for the grid connected converter. For standalone system battery charge controller and batteries are necessary.

CHAPTER 2

SIZING OF SOLAR ARRAY AND BATTERIES

2.1 INTRODUCTION

Before actually implementation of the rooftop solar system on a particular roof or area, the size and cost of system are needs to be calculated. For standalone solar system where no grid power is available, batteries become the essential part of the system. Depends upon the actual load of the site, size of PV panel and batteries are determined.

The following steps are taken to estimate the size of PV panels and batteries

- Calculate available daily average solar energy (irradiation) on the site.
- Calculate total average load of the site.
- Keep some safety load margin.
- Determine module rating required of such load and their arrangement in array to meet load voltage and current demand.
- Calculate number batteries required for no sun time and their connection.

2.2 AVAILABLE SOLAR IRRADIATION ON THE SITE

Suppose a standalone solar system at a particular location is to be installed. Before purchasing the equipment some data are required of that site before buying solar module and inverter. To install a system two rough data are required. Namely:

1. Solar irradiation of that location throughout the year – To calculate the solar panel and battery array size.
2. Tile angle of solar panels – To get the maximum energy form panels. It is obvious that when panels will be facing around 90^{o} from sun, maximum photon will cross the N-layer and photon current will be large. Thus the solar energy will also be more. So to achieve this either of two method can be followed:
    a. Use mechanical sun tracker
    b. Optimize the angle throughout the year.

Using sun tracker for low power system is not economical. Thus tilt angle of solar panels is set to optimum angle. A small house is chosen in Roorkee, utttarakhand as a site to install standalone PV system. The latitude and longitude of Roorkee are 29.8749° and 77.8899° respectively.

2.2.1 Tilt angle of the solar panel

Tilt angle is the angle of solar panels form vertical surface. Out motive is to set this angle to almost equal to 90° towards sun to get most form the sun. To set the tilt angel one need to track the sun path throughout the year. The position of sun can be defined at any time by two angles, namely:

- Azimuth angle: - This is the angle along the horizon, with zero degree corresponding to north and increasing in clockwise manner. Thus 90 degree is east, 180 degree is south and 270 degree is south.
- Altitude angle: - This is the height of sun in sky. This angle is zero at the time of sunrise and reaches up to a maximum value. Altitude is maximum 90 degree for equator. This is also called elevation angle h.

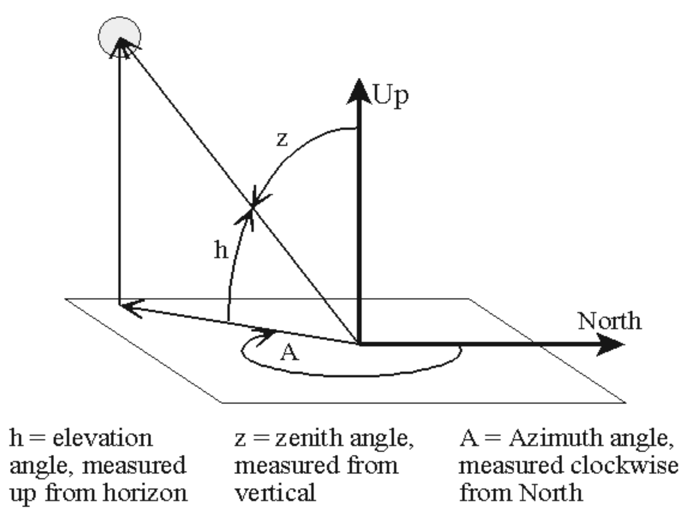

Fig. 2.1 azimuth and elevation angle of sun

Both the angle varies throughout the day. They also depends on the latitude of the particular location and day of the year. Altitude angle h decides the vertical positon of the panels and azimuth angle A decides the horizontal position of sun. A two axis tracker can be implemented based on the two angles to get 100% radiation form the sun. But this is costly task. Also during a day varying the panels according to the azimuth angle does not result in a good improvement from that without it. Only difference is made from altitude angle and one axis tracker is employed if sun tracker is being used.

Now the fig. 2.2 shows the position of sun during a year of arbitrary location in norther hemisphere.

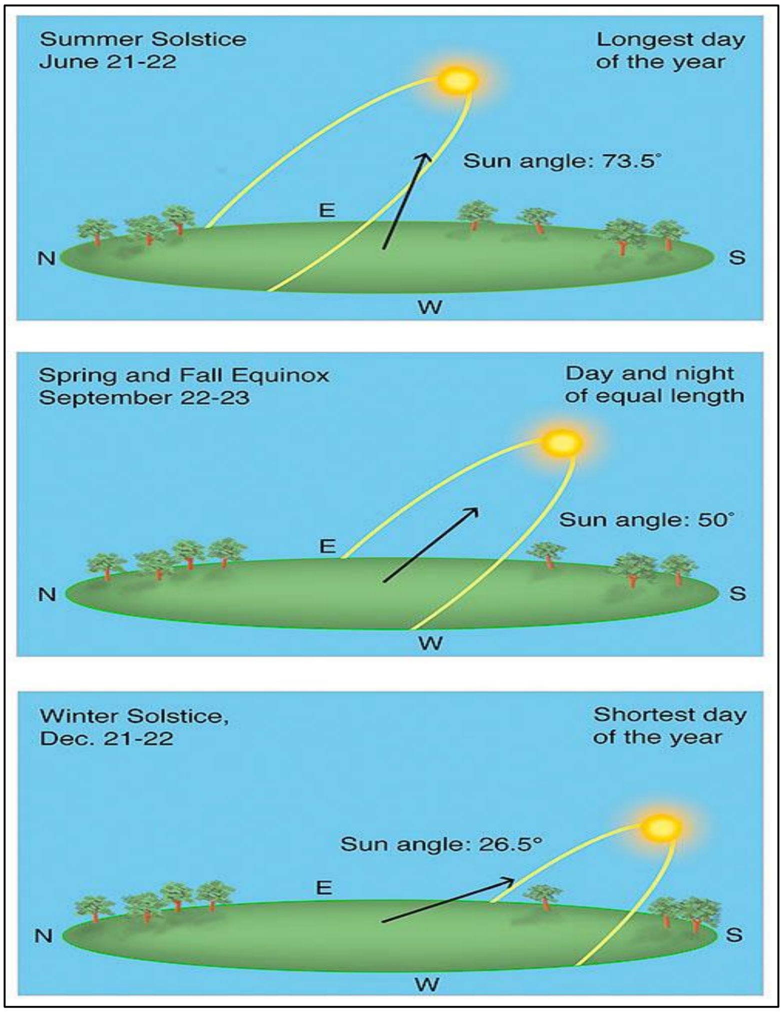

Fig. 2.2 Position of sun in sky during a year

It can be concluded form above figure that altitude angle is high in summer and low in winter. So tilt angle should be large in summer and low in winter. Here tilt angle is measured from vertical position. It is also clear that for a location in a northern hemisphere panels should always face southwards and that in southern hemisphere panels should face northwards.

Fig. 2.3 shows the altitude (elevation) and azimuth angle of sun during December to June.

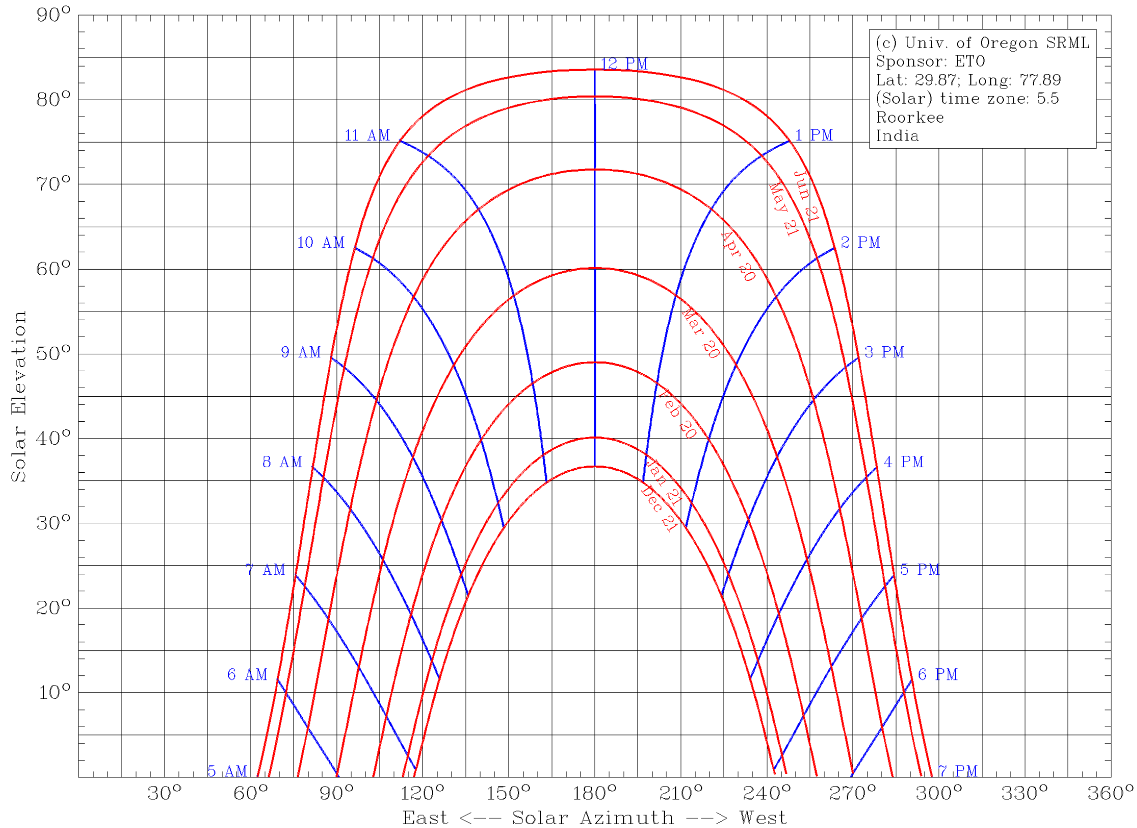

Fig. 2.3 Sun path during June to December on Roorkee

It can be noted form the above figure that for a location in Roorkee maximum elevation angle is less than 90 degree which is obvious as 90 degree can be only on equator and that happens in summer. Altitude angle is only angle which is taking care of. So according to above figure tilt angle may varies between 37° to 84°.

S. no.	Month	Tilt angle(in degrees)
1.	Jan	40 °
2.	Feb	48 °
3.	Mar	60 °
4.	Apr	72 °

S. No.	Month	Tilt angle(in degrees)
5.	May	80^{o}
6.	Jun	84^{o}
7.	July	80^{o}
8.	Aug	72^{o}
9.	Sept	60^{o}
10.	Oct	48^{o}
11.	Nov	40^{o}
12.	Dec	38^{o}

Table 2.1 Month wise Tilt angel at Roorkee

Based on tilt angle in table 2.1 the panels can be varied with the suitable angle. Sun tracker is not being used for small standalone system. Rather than adjusting panels monthly they can be adjusted manually in seasons.

	Fixed	Adj. 2 season	Adj. 4 season	2-axis tracker
% of optimum	71.1%	75.2%	75.7	100%

Table 2.2 Tilting angle Vs % of optimum

It can be seen form the above table that adjusting the panels in 2 season give considerable amount of boost in energy but adjusting 4 times is almost same as adjusting 2 panels. For northern hemisphere these two change can be done on

- March 30 to summer angle – 84^{o}
- September 30 to winter angle -38^{o}

And for only fixed angle tilt angle can be set to 60^{o}.

2.2.2 Irradiation figure at Roorkee

The irradiation is measured in watt/m^2 or watt-hour/m^2/day. It depends upon the location and tilt angle of the surface receiving sun energy. The table below compares the energy received with different tilt angles. This determines the energy produced by panels.

S. No.	Month	Solar irradiation kWh/m^2/day for optimal 60^o	Solar irradiation kWh/m^2/day for adjusted monthly
1.	Jan	5.05	5.40
2.	Feb	5.80	5.99
3.	Mar	6.51	6.51
4.	Apr	6.76	6.90
5.	May	6.63	7.14
6.	Jun	5.90	6.68
7.	Jul	5.04	5.41
8.	Aug	4.71	4.93
9.	Sept	5.50	5.50
10.	Oct	6.19	6.31
11.	Nov	5.80	6.18
12.	Dec	5.10	5.64
	Total	68.99/12 = 5.74	72.59 = 6.04

Table 2.3 Irradiance on Roorkee

Here fix tilt angel is used according to which average irradiance throughout the year is 5.74 kWh/m^2/day. The more calculator can be find in

As a summery following points are to be noted

- In northern hemisphere all panels should face southwards.
- Optimal tilt angel is 60^o.
- Average irradiation or insolation on the location of Roorkee is 5.74kWh/m^2/day.

2.3 Load Demand Estimation

The average estimated load of a particular house is different for different users. Here a load on a virtual house is taken as reference and based on these calculations of solar panels and batteries requirements are done. Again load may depend on season. The worst conditions are taken for calculations.

S. No.	Name of Appliances	Number Of unit	Wattage (W)	Total wattage	Hours	Energy/day (Wh)
1.	LED	4	4	16	8	128
2.	FAN	2	20	40	10	400
3.	T.V.	1	75	75	2	150
4.	Charging point	2	20	40	4	160
		Total		171		838

Table. 2.4 Average daily load of a house

It is clear from the above table that average load demand of such house is **838** watt-hours/day or .838kWatt-hour/day to run the loads mentioned in table. The total load is **171** watt.

Taking a safety margin of **20%**, total load becomes:

$$838 + .20 * 828 = 1005.6 \text{ Watt} - \text{hour/day}$$

2.4 Solar Array Sizing

a solar module PM180 manufactured by CEL India which is having following specifications at STC (1 kW/m^2 and 25^o): -

- Vmpp = 36.0 V
- Impp = 5.0 A
- Pmpp = 180 W

These are the values based on STC. For location in Roorkee current can be adjusted according to the radiation available. Assuming sun hours in a day is 6.

$$\text{Impp} = \frac{5 * 5.74}{6} = 4.78\text{A}$$

Ampere hours available form panels

$$\text{Ah} = 4.78 * 6 = 28.7$$

Ampere hours required

$$= \frac{\text{average load}}{\text{terminal voltage}}$$

$$= \frac{1005.6}{36} = 27.94 \text{ Ah}$$

Parallel strings required to meet current demand

$$= \frac{\text{ampere hours required}}{\text{ampere hours availabe}} = \frac{27.94}{28.7} = 0.973$$

$$= 1 \text{ module in parallel}$$

Thus one module is sufficient to meet load demand and voltage level can be changed by suitable DC-DC converter.

2.5 Battery Bank calculation:-

Average load supplies by batteries each day, assuming batteries supplies for 16 hours, is

$$\frac{1005.6 * 16}{24} = 670.4 \text{ Wh}$$

Taking autonomy of 3 days and depth of discharge 50% watt-hour supplied by battery is

$$670.4 * 3 * 2 = 4022.4 \text{ Wh}$$

Taking battery specification 12V, 100Ah. Adding 2 in series to make voltage 24V.

Ampere hours required form batteries,

$$\frac{4022.4}{24} = 167.6 \text{ Ah}$$

Parallel string of battery,

$$= \frac{\text{ampere hours required}}{\text{ampere hours availabe}} = \frac{167.6}{100} = 1.67 = \sim 2$$

Total 4 such batteries. 2 in series and 2 in parallel.

So overall designed system

- Daily load demand = 1005.6 watt-hour or 1 kW.
- PV module required = 1 (180 peak Watt).
- Battery bank = 4 (12V, 100Ah) – 2 in series and two in parallel.
- Tilt angle of panels 60^o towards south.

CHAPTER 3

PHOTOVOLTAIC ENERGY CONVERSION AND MPPT

3.1 INTRODUCTION

The very first element of the proposed system is the solar array which directly converts the solar irradiation into electric energy. They work on the principle of the photovoltaic phenomenon. The power output from a particular solar array depends on the various atmospheric conditions but the most dominant conditions are solar irradiation and temperature [1]. For a particular irradiation and temperature the power output or terminal voltage and current of the solar array again are not constant but vary with load. Thus solar array characteristic are nonlinear in nature. The power produces is maximum for a particular load. In this chapter first photovoltaic phenomenon is explained in detail then equivalent circuit of solar cell is formed to describe the cell characteristic in terms of equations.

3.2 PHOTOVOLTAIC PHENOMENON

A solar cell is nothing but specially constructed PN diode. When a P type semiconductor is connected with an N type semiconductor recombination of electrons and holes take places. It should be noted that this connection is not merely made by bringing to layer to each other but special process of epitaxial growth etc. are followed. In depletion region there are only immovable positive and negative ions in N and P layer respectively. They formed a voltage drop of around 0.7 volts. As width of depletion region is of order of micro-meter, the electric field generated is very strong. This field restrain the further recombination of the electron hole pair.

Now if anyhow new electron hole pair is generated in depletion region then because of the electric field mentioned above, hole begin to move in direction of field and electron in opposite of it. In photovoltaic phenomenon this electron hole pair is generated by the solar irradiation. When a photon of adequate energy fall nearby junction an electron hole pair is generated. Which under the influence of the electric field move in opposite direction and if the external circuit is closed current starts flowing. This current is called photon current.

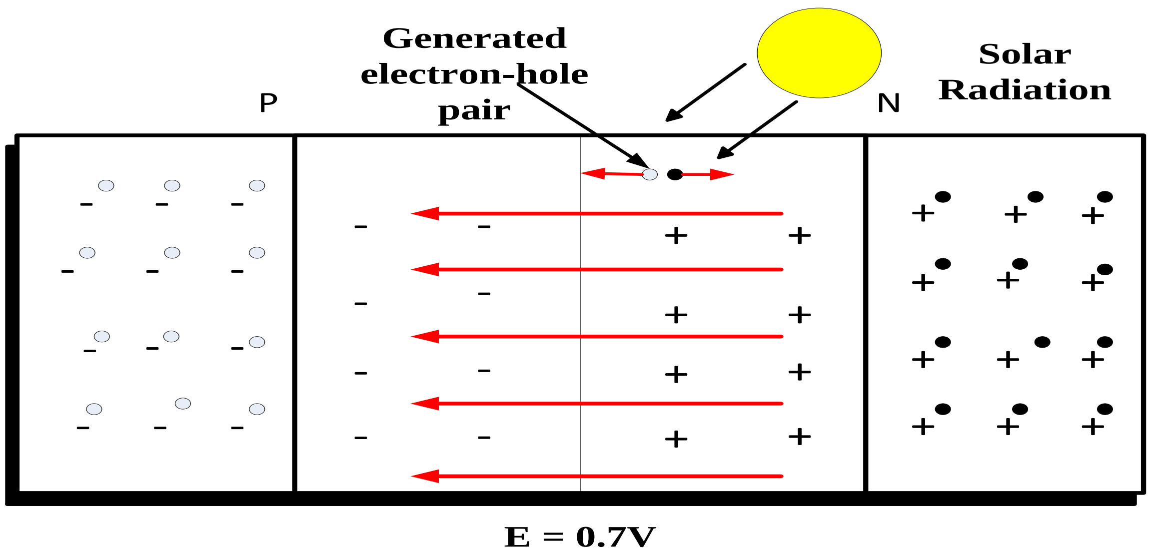

Fig. 3.1 Single Solar Cell

It is mandatory that this new electron hole pair should be generated only in depletion region. Electron hole pair outside the depletion region do not constitute in photon current. Value of photon current depends upon the amount of electron hole pair generated which depends upon the photon penetrating the diode and reaching in depletion region. So a large amount of area is to be exposed to sunlight.

Thus the basic difference between a diode and photodiode lies between the depths of N layer which is thinner in case of photodiode so that photons penetrate the N layer and large amount of them reach to PN junction. This is shown fig. 3.2. Glass cover is employed to protect cell from rain, dust etc.

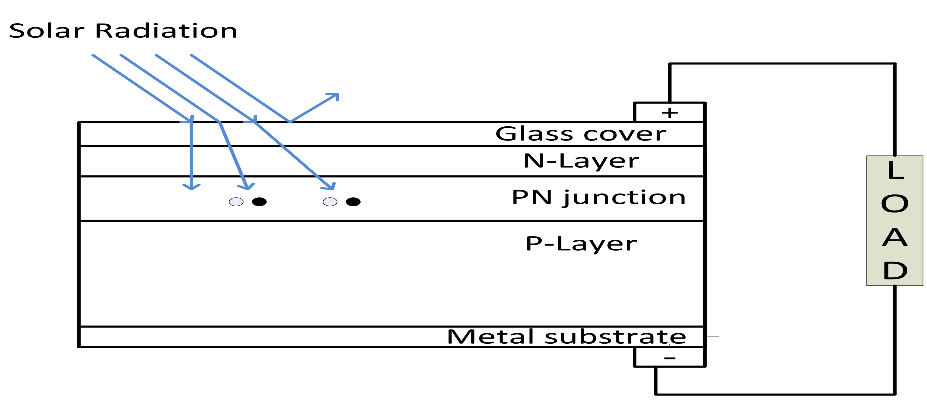

Fig. 3.2 Cross sectional view of solar cell

3.3 CRYSTALLINITY AND STRUCTURE OF SOLAR CELL

Solar cell are generally made from silicon. **Crystallinity** is the property of solid in which atoms or molecules are arrange in a regular and periodic manner. There can be

- **Single crystalline solar cell** in which material is having only one type of regular and periodic arrangement of silicon atoms. The efficiency of such cell is higher in order of 22-25%. But they are costly than polycrystalline due to different manufacturing process.
- **Polycrystalline solar cell** in which materials are divided into region known as grain. Arrangement in grain in regular and periodic but varied form grain to grain. Efficiency is low order of 15%. They are cheaper and used in low power solar system e.g. calculator.

3.4 EQUIVALENT CIRCUIT OF SOLAR CELL

It has been discussed till now that the photon current generated from solar cell depends on primarily on solar irradiation and temperature. This cell work as a current source. The current flows in solar cell is reverse of that flows in convention PV diode i.e. from N layer to P layer and represented as **current source**.

$$I = I_{ph} \tag{3.1}$$

As current comes out of P layer this becomes positive terminal and N becomes negative terminal. This makes the PN junction forward bias and diode current also flows in opposite direction of photon current. This can be represented as **anti-parallel diode** with current source. This reduces current at diode terminal.

$$I = I_{ph} - I_d \tag{3.2}$$

Diode current can be written as

$$I_d = I_o - \exp(V_d/V_t - 1) \tag{3.3}$$

$$V_t = kT/q \tag{3.4}$$

Before collecting this current again some recombination may take place in the photo cell. This recombination results as heat energy and increase the temperature of cell. It can be represented by shunting the current from equivalent **shunt resistance**.

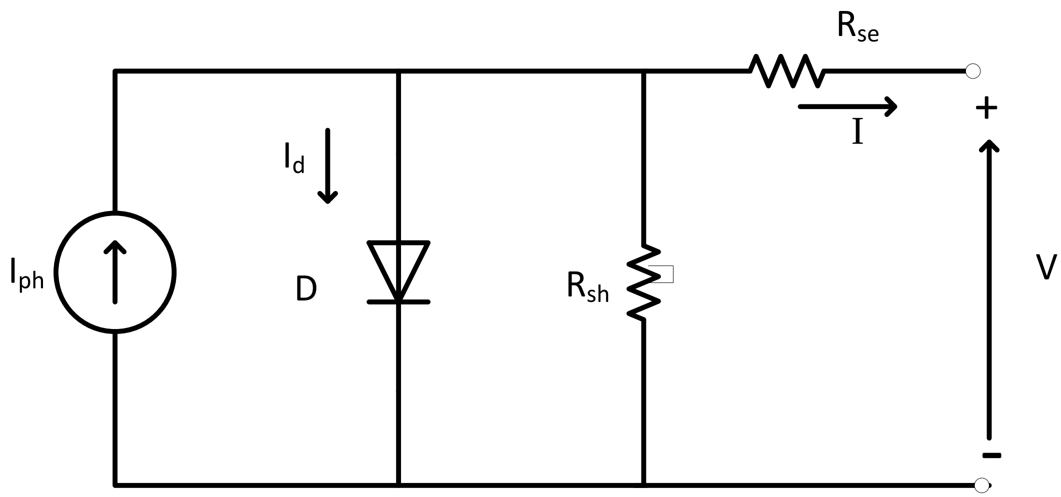

Fig. 3.3 Equivalent circuit of single solar cell

This PV cell material provide some resistance in path of current flow. This with the metal contacts drop can be equivalently represented by **series resistance R_S**. So the equivalent circuit of the cell becomes as shown in fig. 3.2.

When nothing is connected on the terminal of cell this works as a voltage source of around 0.6 to 0.7 volts and shorted by diode. When load is connected three is some voltage drop across this load and diode current depends on that voltage drop.

The final equation of the solar cell is

$$I = I_{ph} - I_o \left[\exp\left(\frac{V+IR_S}{aV_t}\right) - 1\right] - \frac{V+IR_S}{R_{sh}} \tag{3.5}$$

Where,

$$V_t = \frac{N_S kT}{q}$$

$$V_{tn} = \frac{N_S kT_n}{q}$$

$$I_{ph} = \frac{G}{G_n}[I_{phn} + K_i(T - T_n)]$$

$$Io = Ion\left(\frac{T}{Tn}\right)^3 \exp\left(\left(\frac{qEg}{ak}\right)\left(\frac{1}{Tn} - \frac{1}{T}\right)\right) \quad (3.6)$$

$$I_{on} = \frac{I_{scn}}{\exp\left(\frac{V_{ocn}}{aV_{tn}}\right) - 1}$$

The voltage output of the single cell in very low around 0.6-0.7 volts which is not suitable for most of the application. So cells are connected in series to increase the voltage. Generally 36 or 72 cell are connected in series. They have short circuit current about 8 A. The series connected cells are called **PV module**. Several module can be connected in combination of series and parallel to meet the load requirement, and called **PV array**.

The above equation is highly non-linear which can be easily solved by powerful mathematical tools like MATLAB or octave. The power output is

$$P = V * I$$

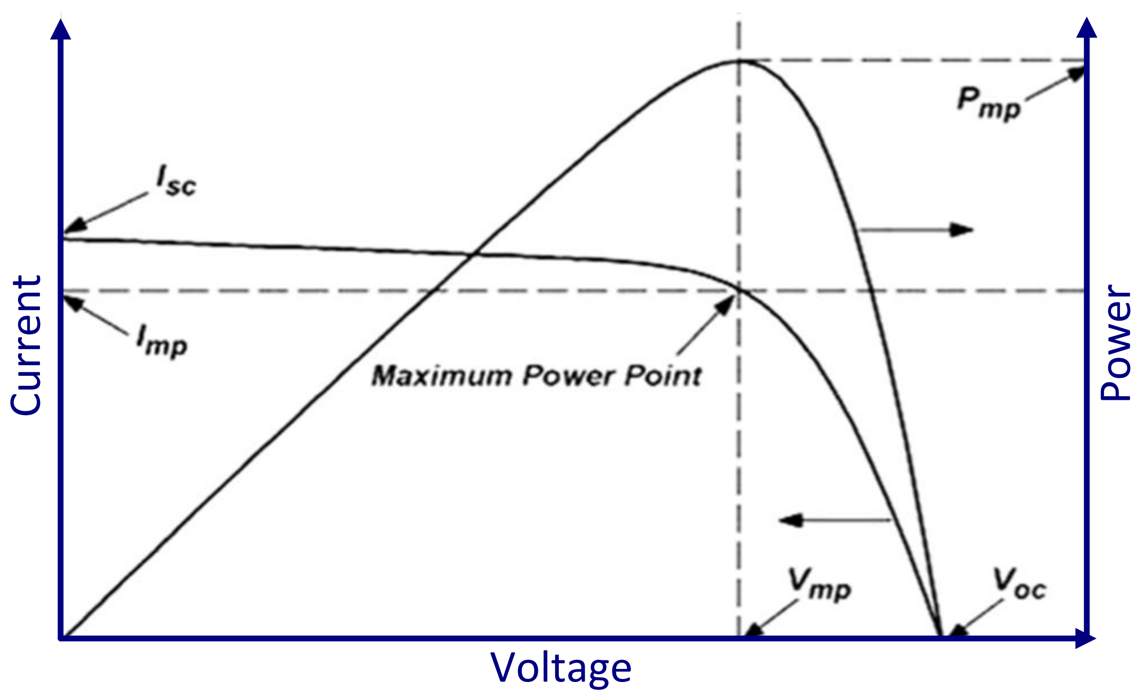

Fig. 3.4 I-V and P-V characteristic of solar module

It is clear from the above fig that power at a particular point is maximum. At maximum power point

$$P_{max} = V_{max} * I_{max}$$

The above characteristics are obtained for constant irradiation and temperature conditions. If irradiation increases the amount of photon reaching PN junction increases which results in more electron hole pair and current output form cell increases. Thus irradiation effects current more than voltage. Similarly if the cell temperature changes which mainly changes cell operating voltage.

3.5 MAXIMUM POWER POINT TRACKING

3.5.1 NEED OF MPPT

There are two major drawbacks of the energy generated form solar photovoltaic. First one is that efficiency of the solar array is very low and second one is the amount of power generated by array is always changing with atmospheric conditions like irradiation, temperature, weather condition, dust etc. The efficiency depends on the manufacturing process and material used which cannot be changed once panel is made. Again even if the atmospheric conditions are constant the power generated depends upon load. For constant weather condition only for a particular load power extracted will be maximum. Our problem is that load cannot be changed again and again to get the maximum power. [2]

Thus PV array is not a constant power source and our goal is to extract maximum power for any load connected with the system. This is the job of Maximum Power Point Tracker (MPPT

3.5.2 WORKING OF MPPT

Maximum power transfer theorem states that to transfer maximum power from source to load source and load impedance must be equal. Thus MPPT is an impedance matching problem. As solar array produces DC here only resistances are considered as loads. A load can be represented in terms of resistance. The operating characteristic or q-point of solar cell set to the point where cell I-V curve meet the load line. In fig 4.1 both PV and load characteristic are represented on the same axes. Let load be R_1 which meets the array curve at operating point 1 which is surely not the maximum power point curve of the array. Now if anyhow this actual load R_L seen by panel is changed to R_L without actually changing R_l then they meet at operating point 2 which is the maximum power extracted from solar panel.

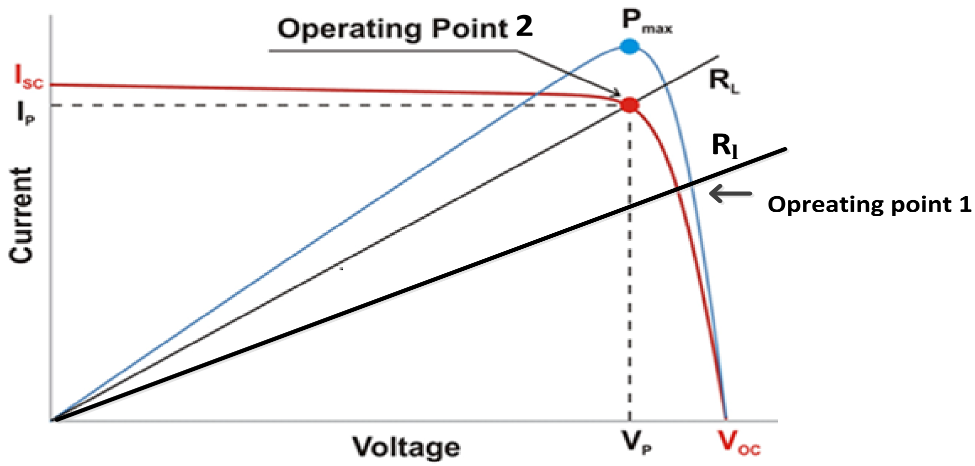

Fig. 3.5 PV and load characteristics

Now our aim is to change the load resistance seen by solar panel to a value where maximum power can be taken. This can be easily done with the help of the DC-DC converter. For different values of duty ratio equivalent input resistance can be different.

DC-DC converters are very high efficient converter. For practical purposes input and output power can be assumed equal. For a buck-boost converter

$$P_i = P_o$$

$$V_i * I_i = V_o * I_o$$

$$\frac{{V_i}^2}{R_i} = \frac{{V_0}^2}{R_o}$$

$$V_o = \frac{D * V_i}{(1 - D)}$$

$$Ri = \frac{(1 - D)^2 * R_o}{D^2}$$

Thus by changing the Duty ratio of the converter to a value corresponding to maximum power point of I-V characteristic, maximum power is delivered to load.

But in practice panel operating conditions are not same. Thus characteristic of solar panel are continuously changing due to irradiation and temperature change. So to track maximum power point some tracking algorithm is required to get the corresponding value of duty ratio.

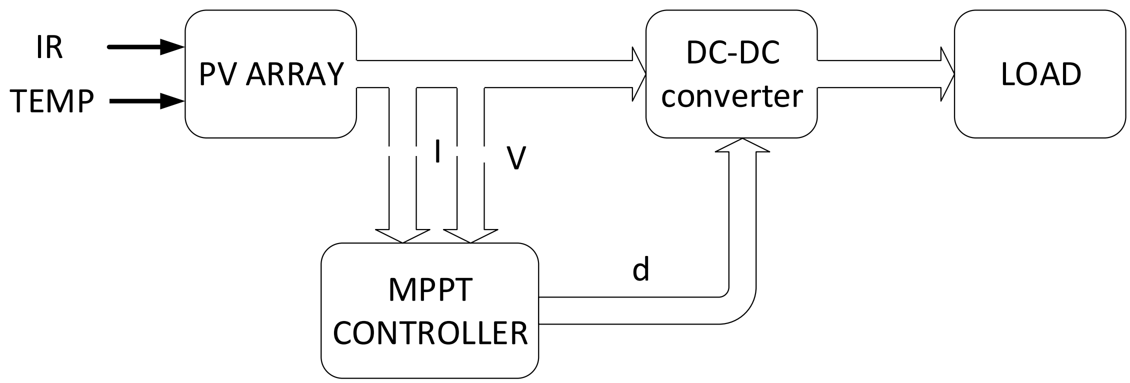

Fig. 3.6 Block diagram of the MPPT system

As shown in block diagram MPPT controller continuously takes the value of panel voltage and current and outputs the regulated duty ratio to DC-DC converter which match the source and load resistances. Thus increasing efficiency of the whole system.

3.5.3 MPPT Algorithms

There are various algorithms proposed in literature for MPPT controller. The variation in irradiation and temperature causes the tracker to deviate from current maximum power point to new maximum power point. Thus tracker needs to response within short period to time to avoid any power loss [3]. The various algorithm vary in sensed parameters, convergence speed, accuracy, implementation complexity, cost and their application. The various algorithm used are:-

1. Perturb and Observe(P&O)
2. Incremental Conductance
3. Fuzzy logic controller
4. Neural network

P&O is very simple to implement and less costly but fail to track exact maxima. There are some oscillations around maxima and fail to track global maxima in case of multiple maxima are there due to partial shading. INC algorithm overcome these shortcomings and ensures the converter by producing PWM pulses to optimize for maximum power transfer whatever the weather and load conditions are. Neural network and fuzzy logic controller are very fast and accurate but neural network requires large training set and complex algorithm and fuzzy logic requires large mathematical calculations which makes them unsuitable for small power system especially for rooftop solar system.

Various controller can be used with above mentioned algorithms to increase speed of convergence. Most commonly used controller are integral controller and PI controller.

3.5.4 Incremental conductance with integral regulator

In this project I have used incremental conductance method with inclusion of integral controller to track the maximum power point. Frist incremental conductance algorithm the role of controller is explained.

Power output from panel is given as

$$P = V * I$$

Taking derivative of above equation

$$\frac{dP}{dV} = I + V * \frac{dI}{dV}$$

At MPP slope of P-V curve is zero, so

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

$$I + V * \frac{dI}{dV} = 0$$

$$\frac{dI}{dV} = -\frac{I}{V}$$

In above equation right hand term is the instantaneous conductance and left hand term is incremental conductance. And MPP is achieved where both conductance are equal and opposite.

At left side of MPP,

$$\frac{dP}{dV} < 0 \quad , \qquad \frac{dI}{dV} < -\frac{I}{V} \quad , \quad \text{increase } V_{ref}$$

At right side of MPP,

$$\frac{dP}{dV} > 0 \quad , \qquad \frac{dI}{dV} > -\frac{I}{V} \quad , \quad \text{decrease } V_{ref}$$

Increment and decrement in V_{ref} is achieved by small change of duty ratio of the DC-DC converter. This small change is known as perturbation size. The procedure is explained completely in the flow chart below.

In flow chart, first form present value and previous of array voltage and current ΔV and ΔI. If $\Delta V=0$ and $\Delta I=0$ that means present atmospheric condition has not changed and system still working on MPP. If $\Delta V=0$ and $\Delta I>0$ the amount of radiation has increased and V_{ref} needs to be increased and vice versa. Similarly in other leg of flow chart decision is taken based on the incremental conductance algorithm discussed above.

Here incremental conductance algorithm is modified to get the required duty ratio. It is desired to set the equation $(I + V * \frac{dI}{dV})$ to zero. This term can be considered as an error and an integral regulator is used to reduce this error. For practical implementation purposes small error margin can be introduced to the maximum power condition and MPP is assumed to occur if the above error is in the error margin.

$$\left[\frac{I}{V} + \frac{dI}{dV} \right] < \epsilon$$

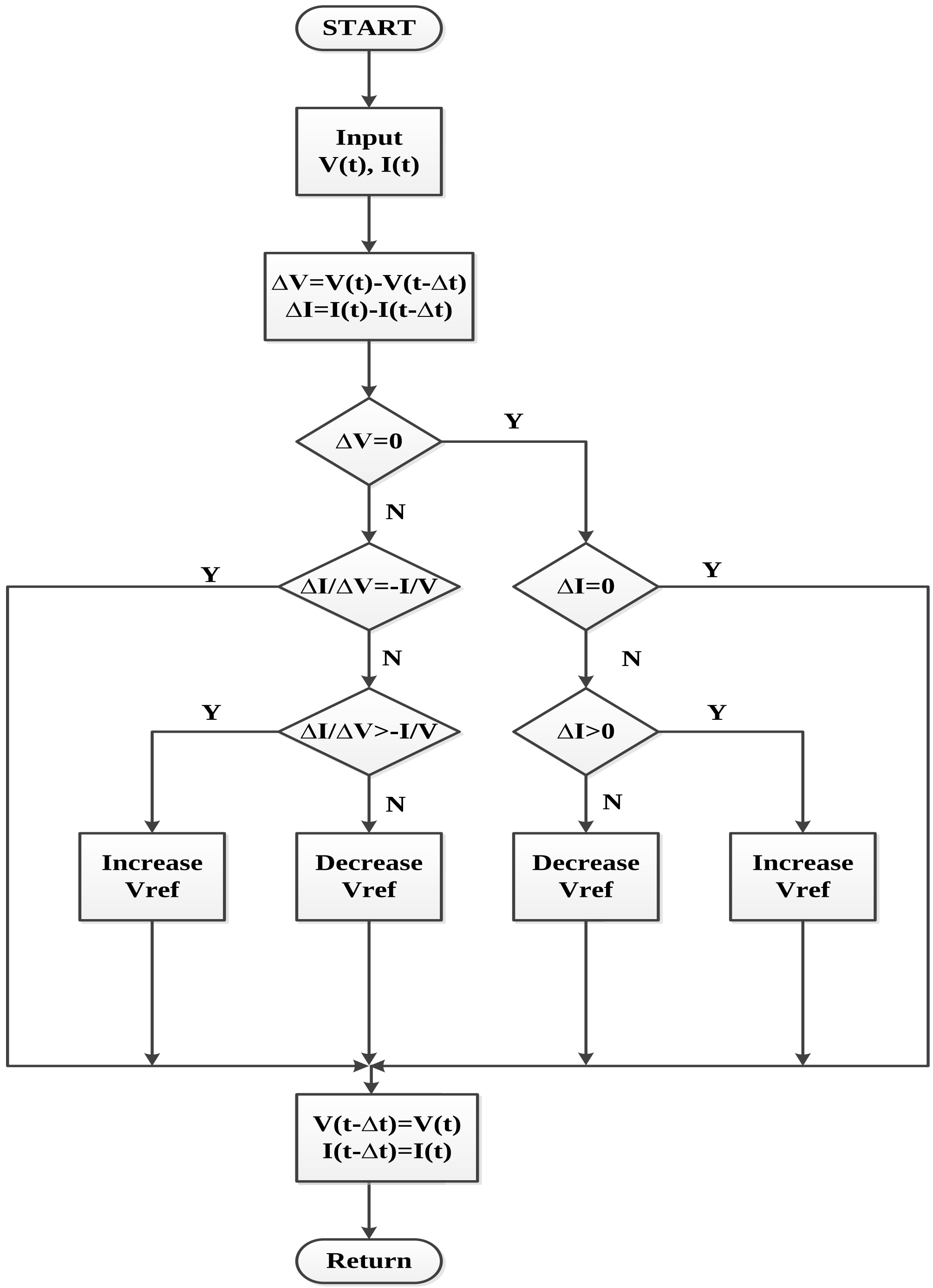

Fig. 3.7 Flow chart of INC algorithm

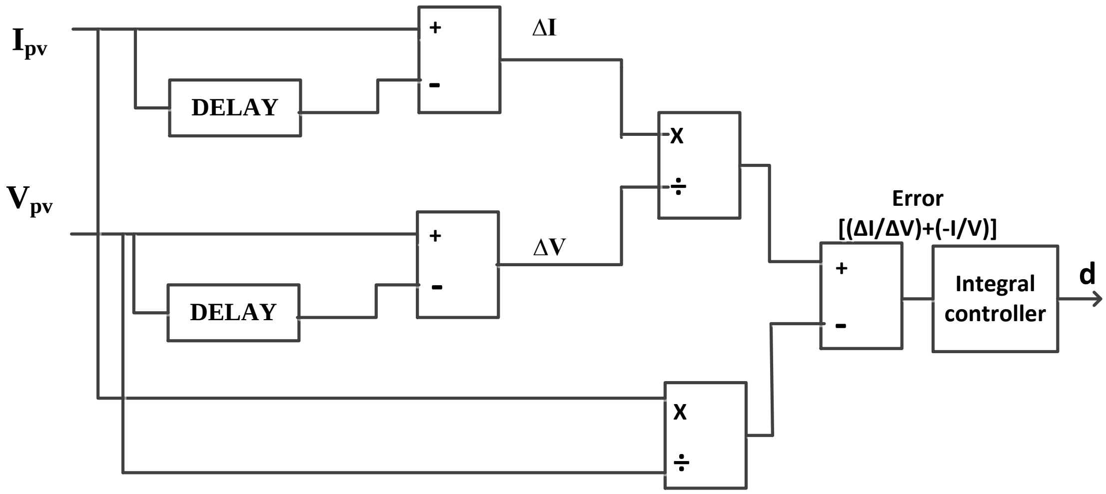

Fig. 3.8 Block diagram of INC with integral regulator

The above error can be further justified as possibilities of not operating exactly at MPP and oscillating around small acceptable value. PWM pulses can be generated and applied to boost converter in order to get maximum power from panels to loads.

CHAPTER 4

CONTROLLER DESIGN FOR DC-DC CONVERTERS

4.1 Introduction

The role of the DC-DC converter has already been discussed in previous chapter. There are various types of converters that can be used. This converter is given PWM pulses from controller. The most commonly used DC-DC converters are

1. Buck converter
2. Boost converter
3. Buck-Boost converter
4. Cuk converter
5. Flyback converter

The most commonly used and simple type of converter is boost converter. It is a power electronics device that used to step up input voltage. Here it is functionally using as an impedance matching device.

4.2 Boost Converter

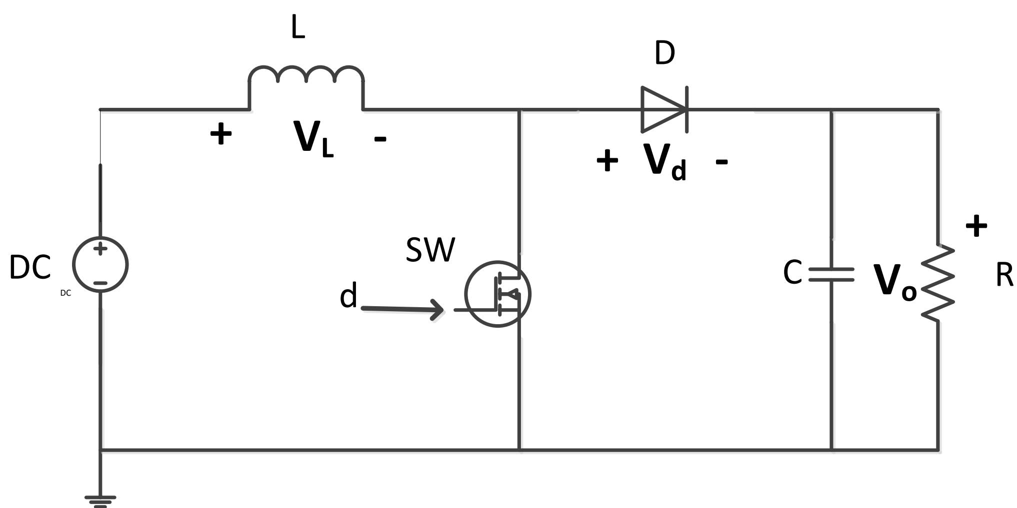

Fig 4.1 Circuit diagram of Boost converter

This circuit can be easily analyzed by using equivalent circuit for switch open and close. Simple KVL and KCL equation are used. Both for switch open and switch close equivalent diagram are as below

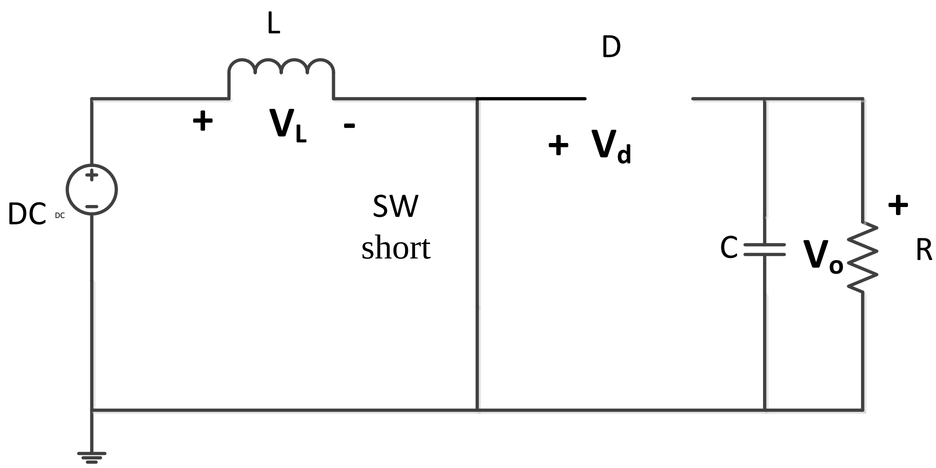

Fig 4.2 Equivalent circuit for switch closed Boost converter

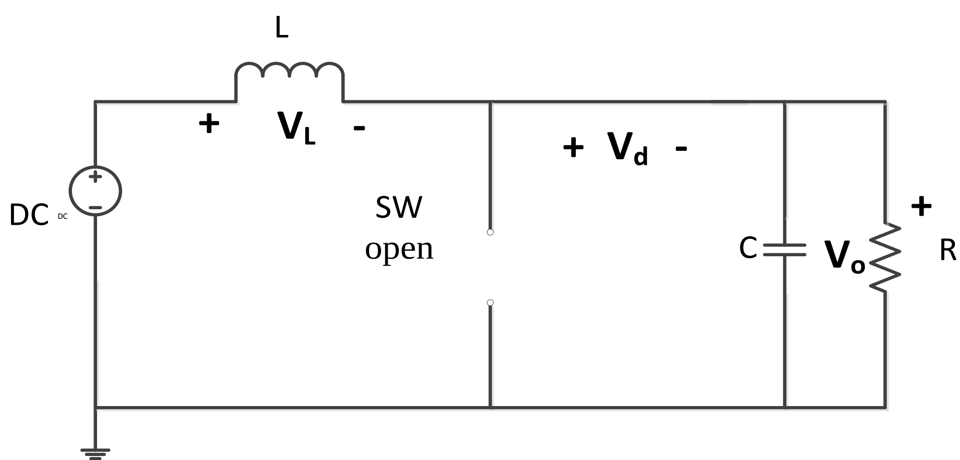

Fig 4.3 Equivalent circuit for switch open Boost converter

Average voltage drop across inductor in a cycle is zero. So

$$V_L = V_S * D + (V_O - V_S) * (1 - D) = 0$$

On solving

$$V_O = \frac{V_S}{1 - D}$$

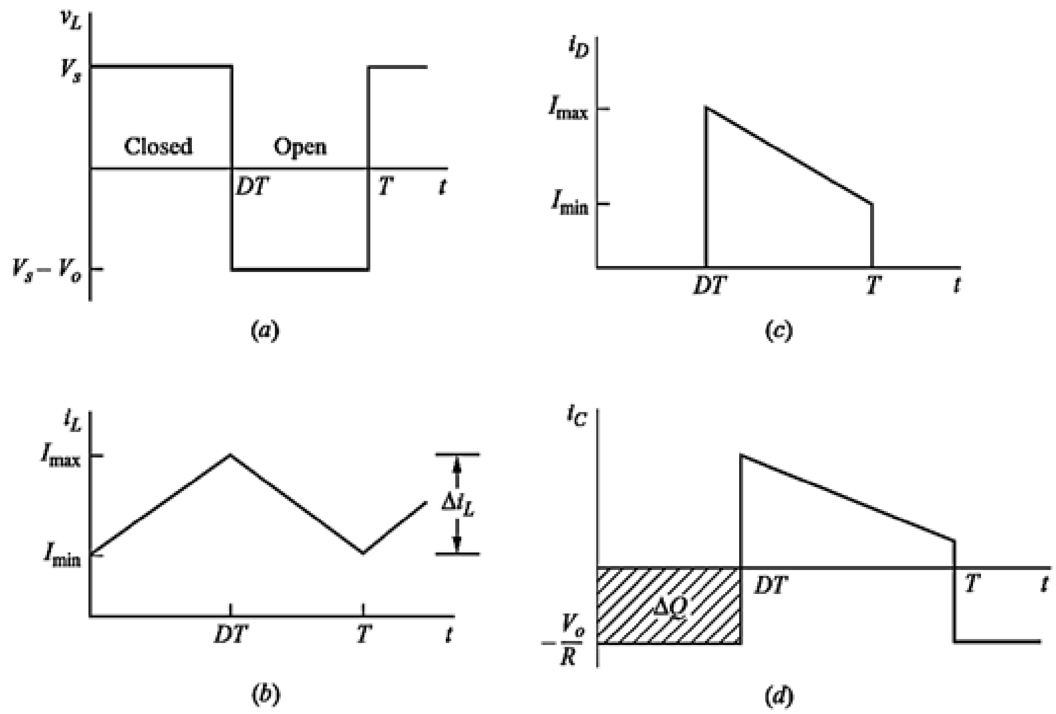

Fig. 4.4 waveforms of the Boost converter

The various waveforms of the boost converter are shown in fig 5.4.

4.3 EQUATIONS USED FOR DESIGNING THE CONVERTER

Designing the converter means determining the values of the inductor and capacitor for a particular switching frequency. To design these values certain values are known.

$$L = \frac{D * (1 - D)^2 * R}{2 * f}$$

$$C = \frac{D}{R * f * \frac{\Delta V_o}{V_o}}$$

$$V_o = \frac{V_{in}}{1 - D}$$

4.4 DESIGNING CONTROLLER USING STATE-SPACE ANALYSIS

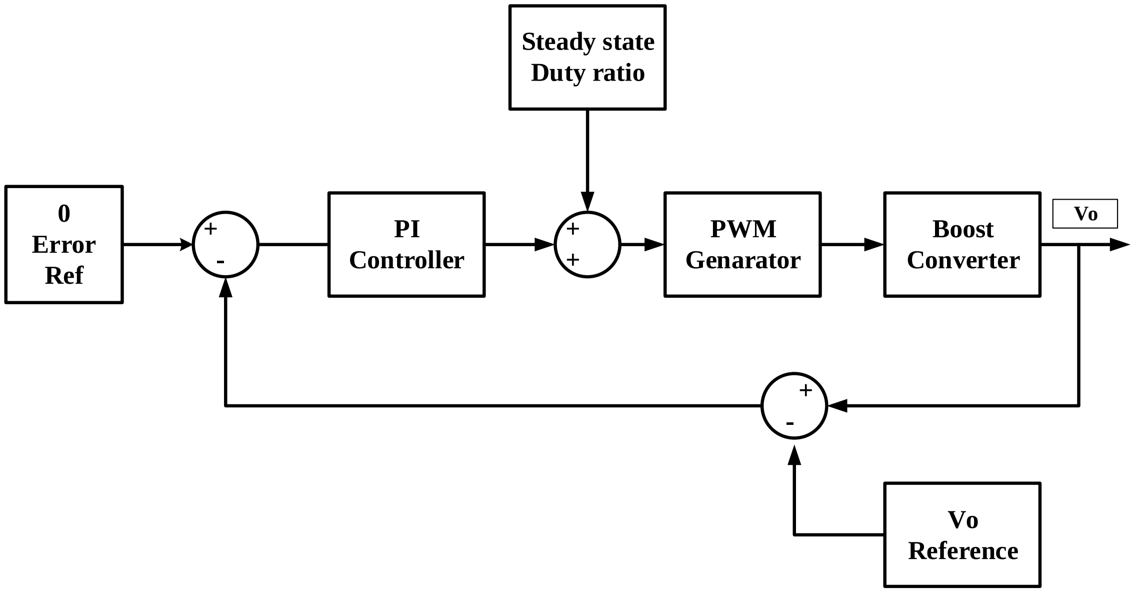

Fig. 4.5 PI controller design for boost converter

Controller's duty is to set the output parameter equal to reference value by making error to zero. For this PID controller is used. Here Ki and Kp are choose such that output tracks the reference input. To evaluate the Kp and Ki transfer function of the system should be known. To design a controller for DC-DC converter state space modelling is done. State space model for complete converter is derived from average of switch on and switch off state space model of boost converter. General equation of state space model is

$$\text{State equation:} \quad \dot{x} = Ax + Bu$$

$$\text{Output equation:} \quad y = Cx + Du$$

Where A, B, C, D are the matrices. x is the state. No of states are equal to the energy storing element. Here y is the controlled output and u is input.

State equations for a period of time when switch is on (for a period of DT_S time),

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \quad (4.1)$$

And output equation,

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{4.2}$$

State equations for a period of time when switch is off (for a period of (1-D)*Ts time),

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{4.3}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{4.4}$$

Both the set of above equation are average over a cycle and averaged state space model in derived.

Average model can be found by

$$A = A_1 * d + A_2 * (1 - d)$$

$$B = B_1 * d + B_2 * (1 - d)$$

$$C = C_1 * d + C_2 * (1 - d)$$

$$D = D_1 * d + d_2 * (1 - d)$$

Where A_1 and A_2 are model matrices for switch on and switch off time.

The average model on solving is,

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{4.5}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{4.6}$$

This is the average large signal model of the boost converter. It consists of small signal model and steady state model. Controller is designed from small signal model. Advantage of small signal model is fast tracking of reference and small size of controller. To derive the small signal model first steady state model is obtained then from large signal model steady state signal model is subtracted. Here goal is to obtain transfer function of output voltage and duty cycle as input to the converter.

$$d = D + \hat{d}$$

Here D is steady state duty ratio and $\hat{d}$ is small signal duty cycle. In steady state put

d = D, $\dot{x} = 0$, $i_L = 0$, $\dot{v}_C = 0$, $v_{in} = V_{in}$. Steady state model is derived as follows.

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix}$$

Now, subtract the above steady state model form the large signal model and by simple mathematics obtain the small signal model as follows:

$$\begin{bmatrix} \hat{\dot{i}}_L \\ \hat{\dot{V}}_c \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} \hat{il} \\ \hat{vc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{Vc}{L} \\ 0 & -\frac{I_L}{C} \end{bmatrix} \begin{bmatrix} \widehat{Vin} \\ \hat{d} \end{bmatrix}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{i}_L \\ \hat{V}_c \end{bmatrix}$$

Now form the small signal model one can obtain transfer function by the following equation

$$\frac{V_o(s)}{V_{in}(s)} = C(sI - A)^{-1}B + D \qquad (4.7)$$

Where

$$A = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} \quad B = \begin{bmatrix} \frac{Vc}{L} \\ -\frac{I_L}{C} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad D = [0]$$

And to get

$$\frac{V_o(s)}{\hat{d}(s)} = C(sI - A)^{-1}B + D$$

Where

$$A = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix}, B = \begin{bmatrix} \frac{V_o}{L} \\ \frac{-I_g}{C} \end{bmatrix}$$

$$C = [0 \quad 1], D = [0]$$

The above equation can be easily get in pole zero form in one line code in MATLAB scripts:-

```
>>  T_F = zpk (tf (ss (A,B,C,D)));
```

The following values are used for designing the boost converter:-

Vin = 108, Vo = 400, L = 0.6mH, C = 10uF , R = 296.2

On solving in MATLAB

$$T\_F = \frac{v_o(s)}{\hat{d}(s)} = \frac{-5.4248e05 * (s - 3.66e4)}{s^2 + 366.2 * s + 1.34e07}$$

It can be verified by Simulink model of above transfer function.

Once transfer function is known then using PID tuner is MATLAB one can determine Kp and Ki values to be tuned for designed values. PI controller can be tuned using a inbuilt app of MATALB PID tuner using following command:-

```
>>  pidTuner(T_F);
```

It then pops a window which shows response of the tuning parameter. Value of Kp and Ki can be easily from the window. For the above mentioned transfer function Kp = 0, Ki = 0.10748 Rise time = 0.0138 sec. and Settling time = 0.0249 seconds.

CHAPTER 5

BATTERY CHARGE CONTROLLER, INVERTER, FILTER AND GRID CONNECTION

5.1 USE OF BATTERIES

Batteries are the important part of the standalone system. Batteries are used mainly for two purposes:

- Sun is not available during nights so batteries work as a source during nights. Also when load is greater than the maximum power available from array both solar array and batteries supplies the load.
- When load is less than maximum power of array we cannot maximize the efficiency of solar array. Batteries work as dummy load here and charging of battery occurs.

Battery life depends upon the charging and discharging of it. So in order to increase the life span of battery and for a safety margin it's charging and discharging is controlled by **charge regulator** or **battery charge controller**.

A battery charge controller limits the rate at which electric current is added or drawn from batteries. It has two controller. One is on array side to control charging and one is on load side to controller discharging. Some important functions performed by this controller are:

- **Prevent Battery Overcharge**: Battery has a specification named as State of Charge (SOC) which shows the current power stored in battery with respect to the fully charging condition and when SOC is 100% battery has to disconnect form source for safety and **life** issue.
- **Prevent Battery Over discharge:** to disconnect the batteries form load when batteries reaches low SOC around 30-40%.
- **Controls the battery charging and discharging rate:** Batteries are charged at constant voltage but charging current may vary according the power available. There is a limit of charging current. A 12v, 100amps battery can be charged and discharged with maximum 100 amps.

- **Provide Load Control Function:** To automatically connect and disconnect an electrical load at a specific time.

5.2 Charge Controller Types

There are three basic types of charge controller

- Shunt controller
- Series controller
- PWM controller

5.2.1 Shunt controller

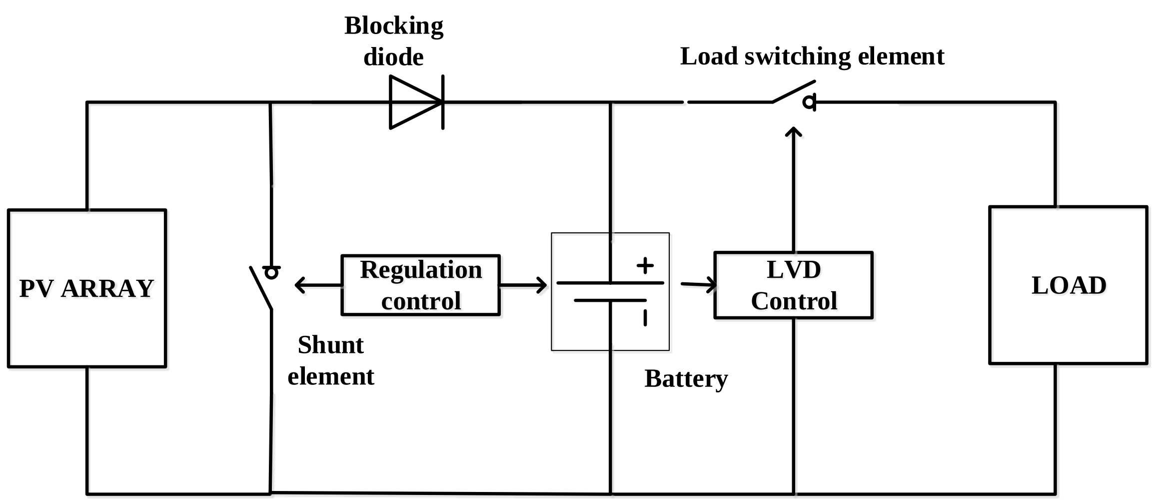

Fig 5.1 Shunt controller

Shunt controller consists of a blocking diode in series between the battery and the shunt regulation element to prevent the battery from short circuiting when the module is regulating. When switch is on PV array shorts and no power flow form source to load.

5.2.2 Series controller

In a series controller, a relay or solid-state switch either opens the circuit between the module and the battery to discontinuing charging, or limits the current in series-linear manner to hold the battery voltage to a high value. In simple series interrupting design, the controller reconnects the module to the battery once the battery falls to the module reconnect voltage set point. Fig 6.2 shows the series controller.

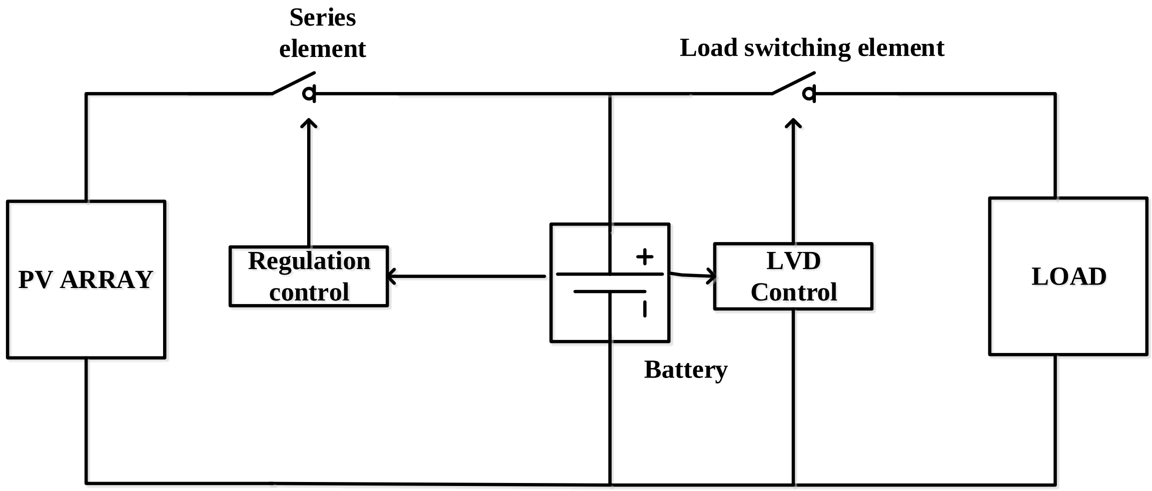

Fig. 5.2 Series Controller

Series controller does not need any series diode and algorithm are easy to apply.

5.2.3 Pulse Width Modulation

This method uses solid state switches to apply pulses of current at a high frequency, but vary with a variable duty ratio cycle. Duty ratio is such that to control the desire variable such as battery receiving constant charge from battery.

In a 12 V battery terminal voltage vary between 10.5 and 14.5 V, depending on the actual SOC of the battery, charging current, discharging current, age and type of the battery. When a normal fully charged battery and no charging or discharging current is flowing than the battery terminal voltage is between 12.4 and 12.7 V. Battery has some equivalent resistance in series with it. When charging current is flowing terminal voltages jump to a higher level depending on the current e.g. 13.4 or 13.7, when loads are switched on the voltage drops down to a lower level also depending on the current e.g. 11.8 V or 12 V. The PV module produces energy and the current is flowing into the battery so voltage level increases up to the range of 14.4 V, then the overcharge protection starts the work. When the battery voltage level is 14.4 V, the charge controller is switched off the charging current or reduce it by pulse width modulation. To disconnect the system loads once the battery reaches a low voltage or low state of charge condition. If the voltage of the system falls below 11.5 V for a period of minimum 20 s than the charge controller will be switched off for minimum 30 s. All loads which are connected to the controller is off. If the battery voltage increase above 12.5 V for more than 20 s than the charge controller will be switched ON the loads again for a minimum time of 30 s. The delay of 30 s is integrated to protect the system against a swinging situation.

5.3 INTRODUCTION TO INVERTER

Most of the loads use AC supply for their operation. So a DC-AC inverter is required to convert the DC voltage and current available form PV panel to AC values without much loss of power. Single phase inverter is used in various home application such as UPS, power source, standalone solar system etc. The single phase inverter can be derived in half bridge and full bridge structures. The main function of the inverter is to provide AC output voltage of desired frequency without much distortion in under both linear and nonlinear load. The inverter can be divided into again two types

- Transformer less and
- Transformer based.

Transformer less full bridge inverter though are compact size, lower cost but fail to provide isolation between source and load. Transformer based inverter used mainly to provide galvanic isolation between load and source. For grid connected system there is a problem of leakage current due to neutral involving. This is solved in transformer less inverter by using H5 and HERIC topology. The output of the inverter is in form of pulses contain harmonics of higher order. These harmonics need to be subtracted by using low pass filter. Filter size depends upon the lowest order harmonics needs to be subtracted and voltage rating. Higher the order of harmonics smaller the size of filter is. Lowest order harmonics depends upon the type of modulation used for inverter operation. For standalone system simple bipolar or unipolar topology can be used. Difference lies between the pulses pattern given to switching devices. A full bridge inverter consists of four switches either MOSFET or IGBT with feedback diode anti parallel with each switch.

SPWM pulses are having the following advantages.

- Reduced power losses

- Easy to generate

For generating PWM pulses sinusoidal reference is compared with high frequency triangular pulses using digital microcontroller. The desired pulsed have the following characteristic:

- Linearity of voltage control
- Low switching losses in inverter structures
- Low amplitude of lower order harmonics to minimize filter requirement and THD of output voltage and current.

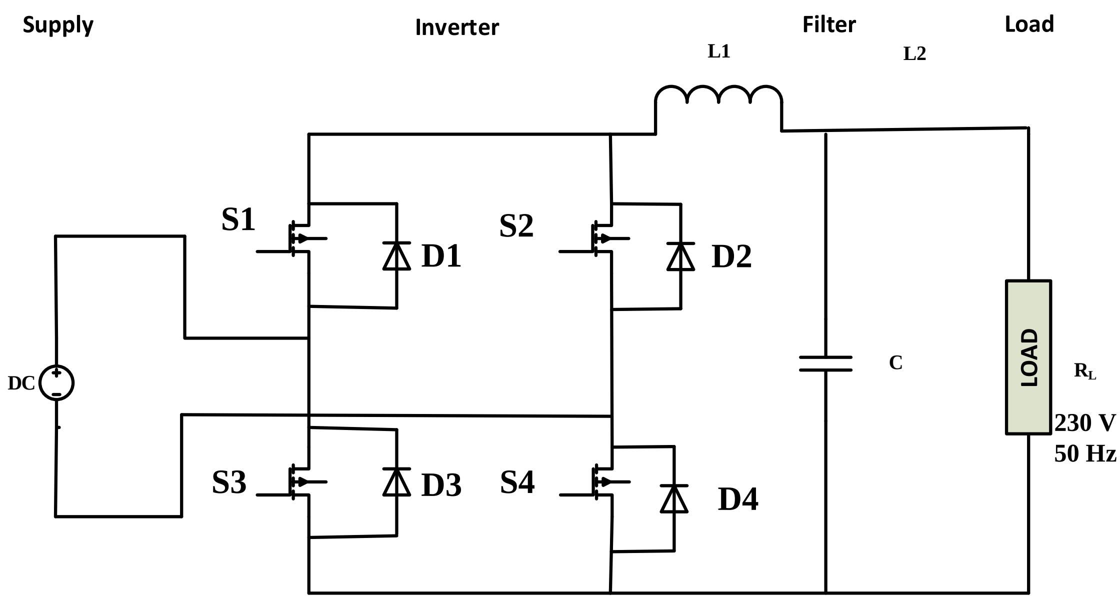

Fig. 5.3 H-Bridge single phase Inverter topology with low pass filter

There are two basic topologies to generate sinusoidal PWM that control the output of the inverter:

- Bipolar PWM
- Unipolar PWM

5.3.1 BIPOLAR PWM

The upper and lower switch in the same inverter leg work in a complementary manner with one switch turned on and other turned off. Thus only two independent source are required to generate by comparing one sinusoidal signal with triangular carrier wave.

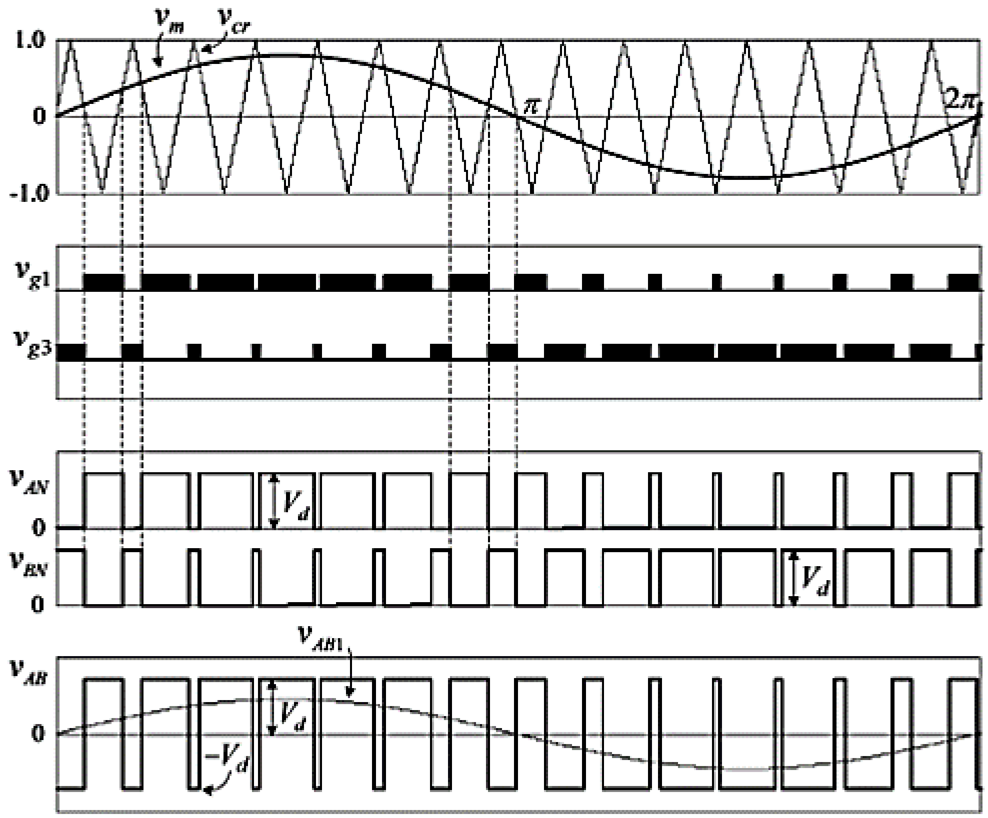

Fig. 5.4 Waveform of bipolar modulation scheme

The inverter terminal voltage is denoted by V_{BN} and V_{AN} and inverter output voltage is $V_{AB}= V_{AN}-V_{BN}$. Since the waveform of V_{AB} switches between positive and negative dc voltages this scheme is called bipolar PWM.

5.3.2 UNIPOLAR PWM

The unipolar modulation normally requires two sinusoidal modulating waves of same magnitude and frequency but 180° out of phase. The two waves are compared with same triangular carrier wave generating two gating signal. These gating signals are applied to the upper switches of the inverter and corresponding lower switches are triggered by inverting the gate signal of respective upper switch. The inverter output switches between 0 to +V_{DC} and 0 to -V_{DC}. That's why this modulation is called unipolar modulation scheme.

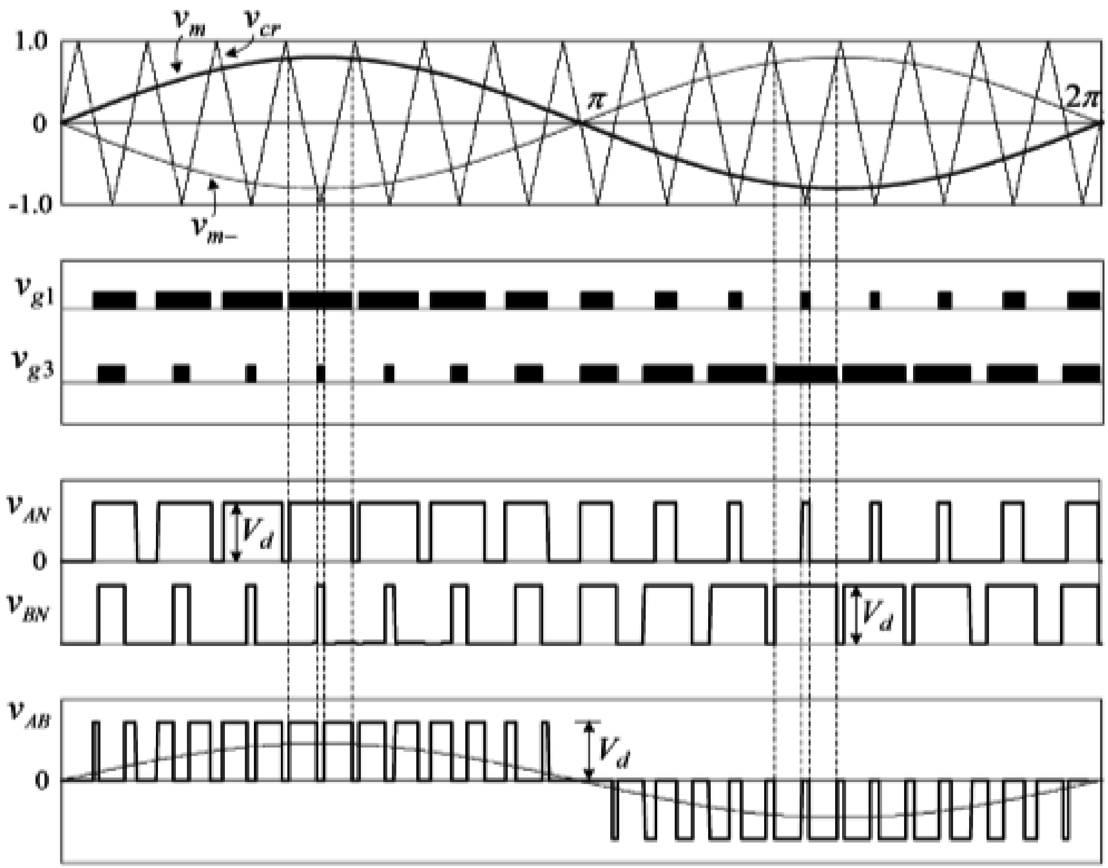

Fig. 5.5 Waveform of unipolar Modulation scheme

As shown in figure output of inverter is not purely sinusoidal but contains harmonics. To get pure sine wave low pass filter is used [4].

5.5 Design of Passive, Low pass, Second-order filter

To filter out the unwanted frequency from the inverter output a low pass filter is used. Passive low pass second order filter. By using unipolar modulation the order of harmonics is as follows:

$$h = a * m_f \pm b$$

Where, h = order of harmonics present and m_f = frequency modulation, If a = 1, 3, 5… then b= 0, 2, 4, 6…

And if a = 0, 2, 4, 6… then b =1, 3, 5…

So lowest order harmonics is

$$h = m_f - 2$$

This frequency is set as a cut off frequency. Higher the frequency smaller the component will be. A low pass filter is to be designed to filter out all frequencies other than fundamental as shown in fig 7.4.

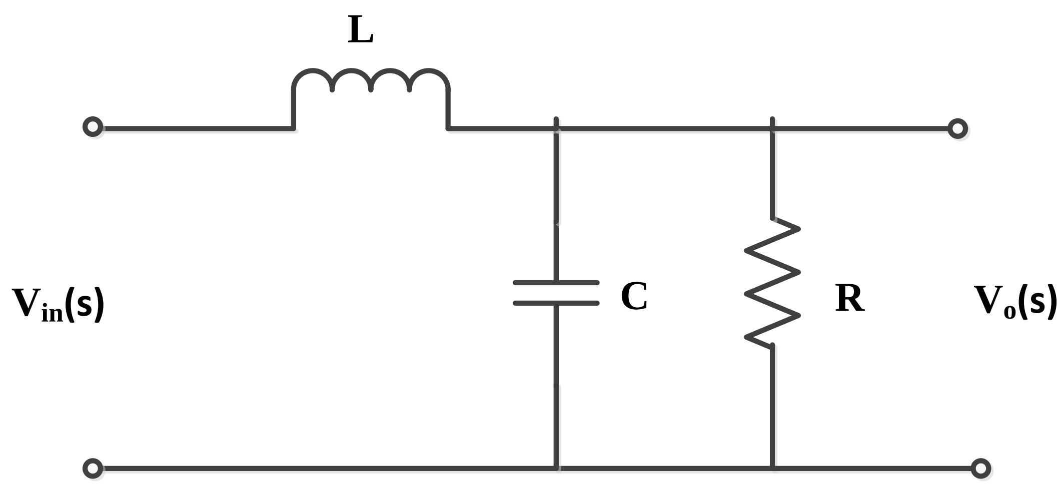

Fig. 5.6 Second order low pass filter.

Analysis of the circuit using complex frequency variable, s gives

$$T(s) = \frac{V0}{Vin}(s) = \frac{\frac{\frac{R}{sC}}{R + \frac{1}{sC}}}{sL + \frac{\frac{R}{sC}}{R + \frac{1}{sC}}}$$

$$T(s) = \frac{\frac{1}{LC}}{s^2 + \frac{s}{RC} + \frac{1}{LC}}$$

Standard low pass filter equation

$$T(s) = \frac{T(0)w_0{}^2}{s^2 + \left(\frac{wo}{Q}\right)s + w_0{}^2}$$

Comparing filter equation with the standard second order equation,

$$wo = \frac{1}{\sqrt{LC}}$$

And T(0) is gain of DC component,

$$T(0) = 1$$

And

$$Q = R\sqrt{\frac{L}{C}}$$

Poles of filter are

$$s_1, s_2 = -\frac{1}{2RC} \pm \left(\frac{1}{2}\right)\sqrt{\left(\frac{1}{RC}\right)^2 - \frac{4}{RC}}$$

To be a stable system poles should be in left part of s-plane. For this,

$$\left(\frac{1}{RC}\right)^2 - \frac{4}{RC} < 0$$

$$4R^2C > L$$

Here Q quality factor denotes the sharpness of frequency response near cut-off frequency range. Which is generally taken below .707 for this type of application. The slope of this second order low pass filter is 40dB/decade. Based on above equation value of R, L and C can be determined.

5.6 GRID CONNECTED INVERTER CONTROL

Large power solar plant can be connected to grid to supply the additional power to grid utility. No batteries are required. Before connecting to grid output voltage and frequency must meet the grid requirement. Input of inverter is set to a reference value and using PI controller current reference is generated. After connecting boost converter three phase inverter and inverter control are required. The following steps are employed:-

- Output of boost converter control (Vdc control).to generate current reference
- ABC to dq transformation of three phase voltage and current.
- Feed forward equations to generate modulation index
- PI controllers

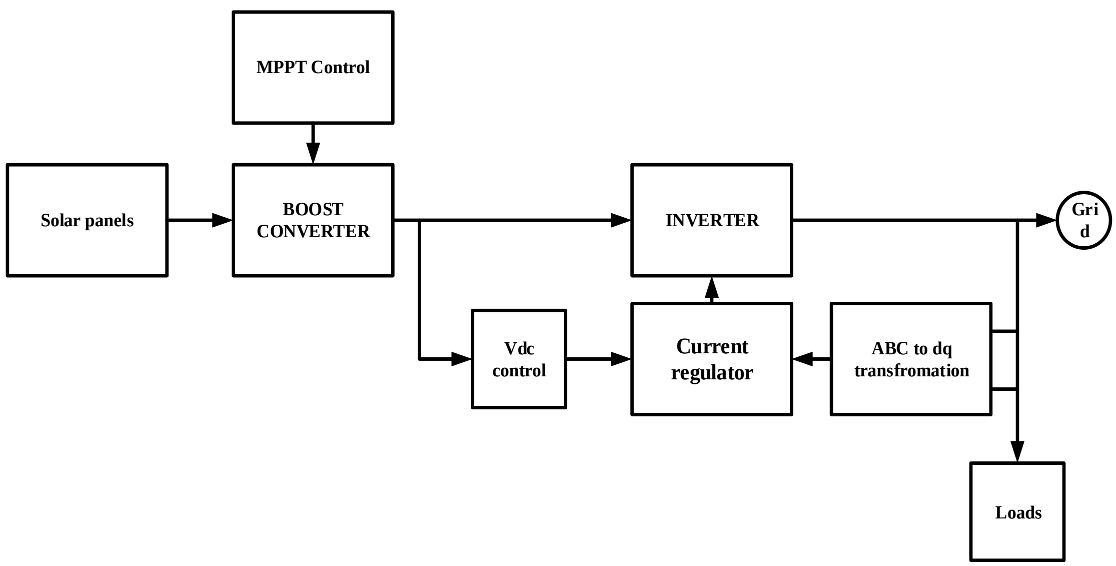

Fig. 5.7 Grid Connection Control Block diagram

CHAPTER 6

SIMULATIONS AND RESULTS

This chapter includes all the simulation diagrams of system mentioned in previous chapters and their results simulated in MATLAB environment. This chapter includes outputs of

- Solar module (180 watt)
- DC-DC converter for MPPT
- MPPT results for different irradiation
- Dc output 220 Volts and Inverter output AC of 230V and 50 Hz.

6.1 Solar Module

Based on equations defined in chapter 3 following module can be simulated in MATLAB. The specifications of a module at STC (25^o and $1000 w/m^2$) are:

Manufacturer: CIL India Ltd.

Module name: PM180

V_{mpp} = 36.0V, I_{mpp} = 5.0A, V_{oc} = 44.8V, I_{sc} = 5.30A

P_{max} = 180 watt.

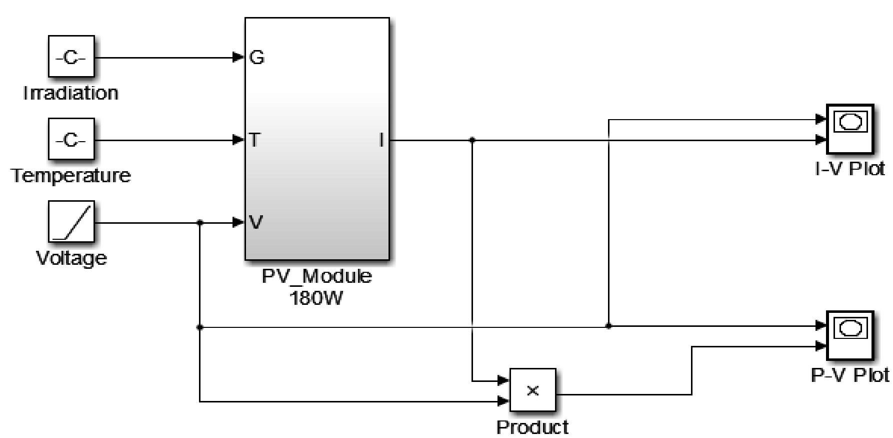

Fig. 6.1 Simulation diagram of solar module 180 watt in MATLAB

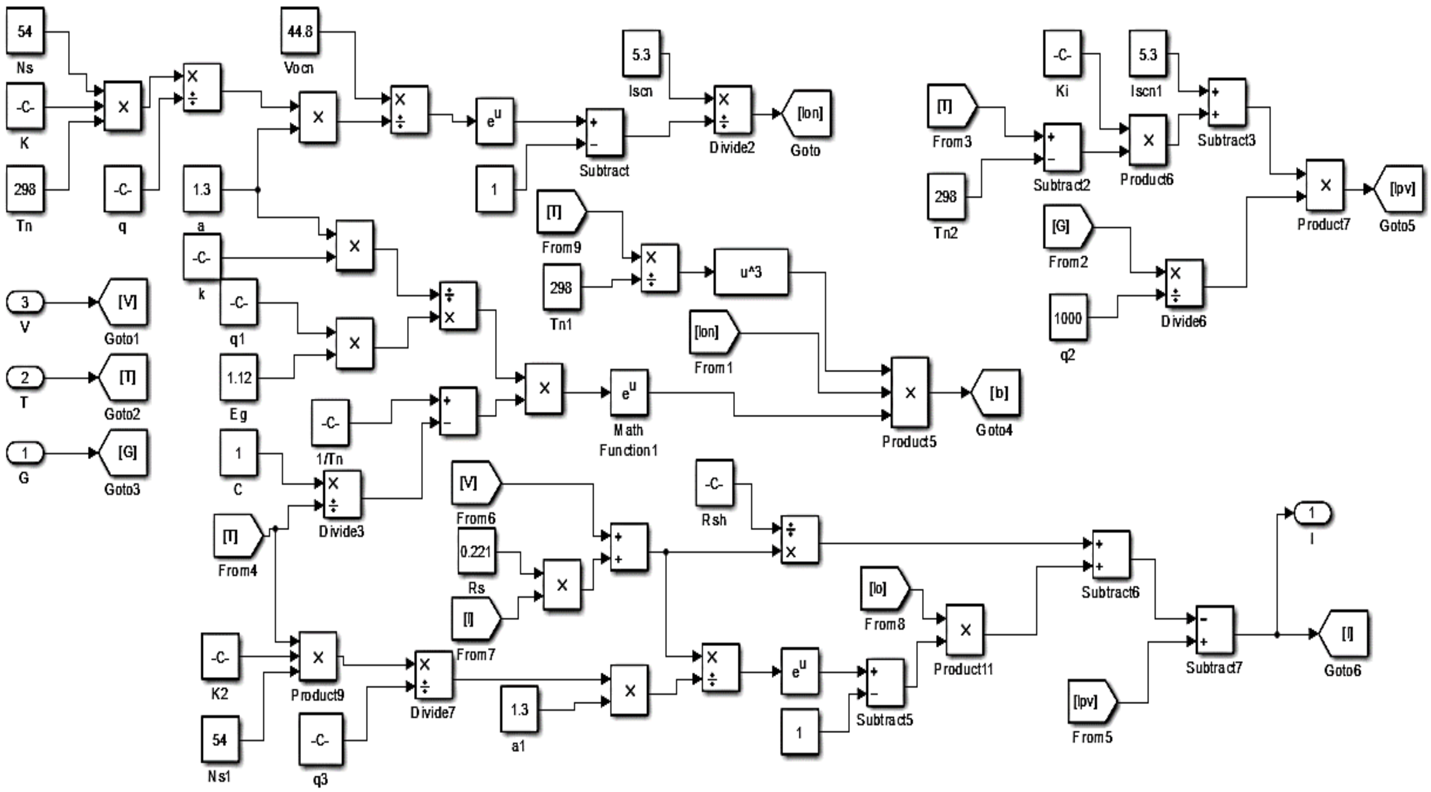

Fig. 6.2 Simulation of solar cell equation in matlab

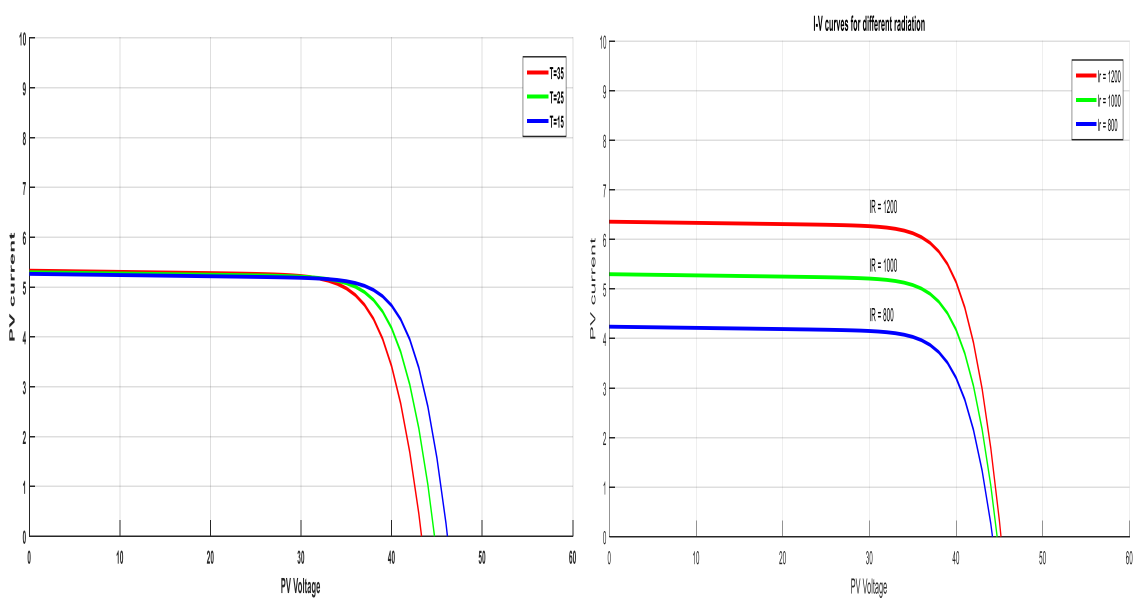

Fig. 6.3 I-V Curve of solar module for different Temperature and Irradiance

6.2 Close loop DC-DC converter

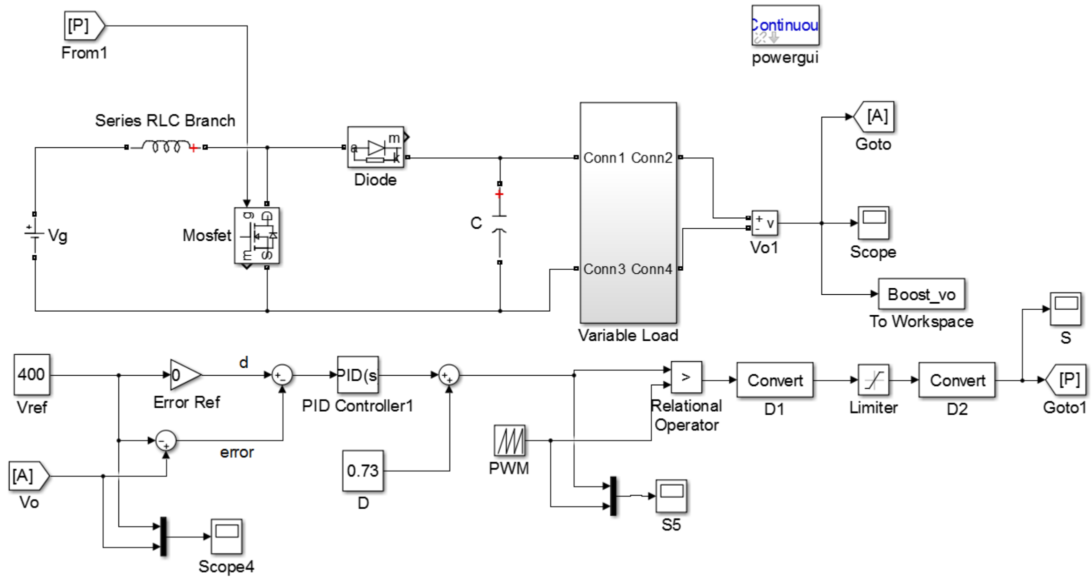

Fig. 6.4 DC-DC boost converter

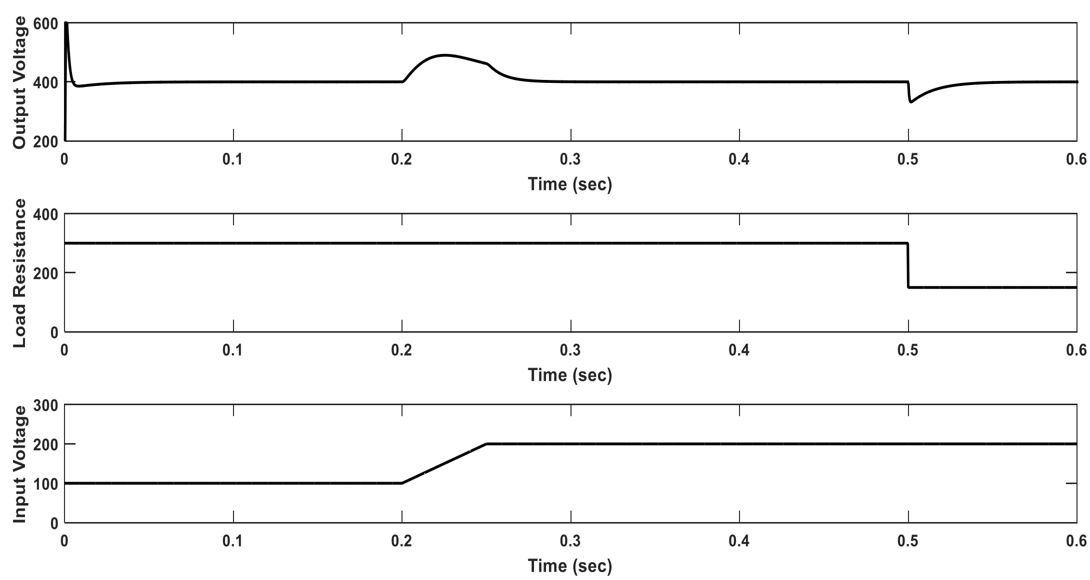

Fig. 6.5 Output of boost with load and line regulation

Based on the equation defined in chapter 5, the following values are calculated for boost converter. Known values are: Switching frequency = 10000 Hz, Input voltage = 108V, Output voltage = 400V, Power = 540 watt.

Calculated value

D = 0.73 for steady state otherwise controlled by MPPT algorithm,

L=0.6e-3H, C= 10e-6F, R= 300 ohm and 150 ohm

6.3 MPPT

Incremental conductance with integral regulator is explained in chapter 4.

Here value of integral constant is set to 5.

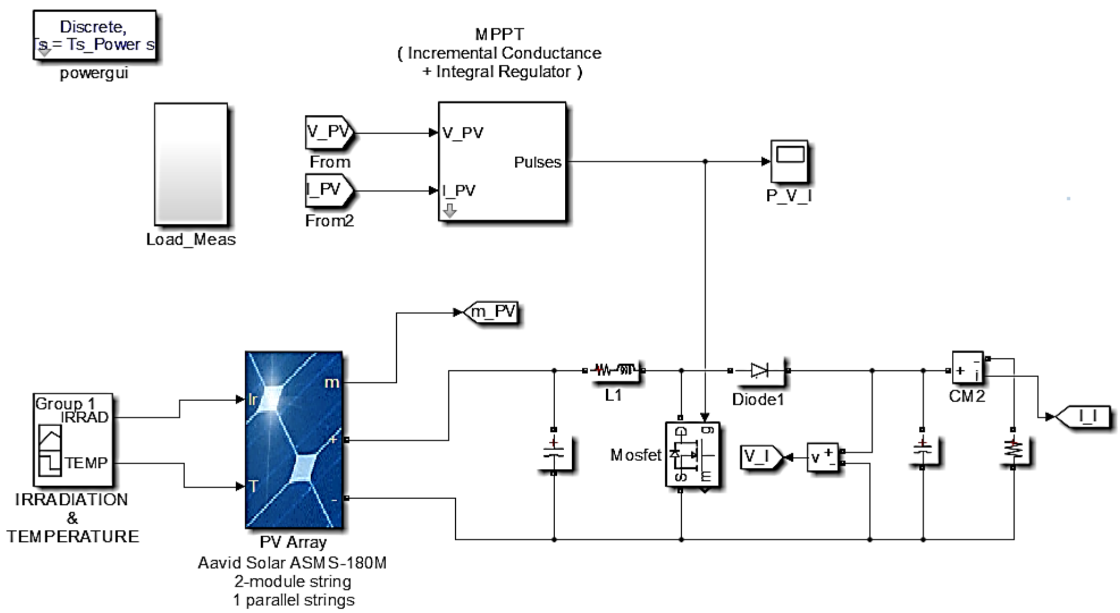

Fig. 6.6 MPPT circuit in MATLAB

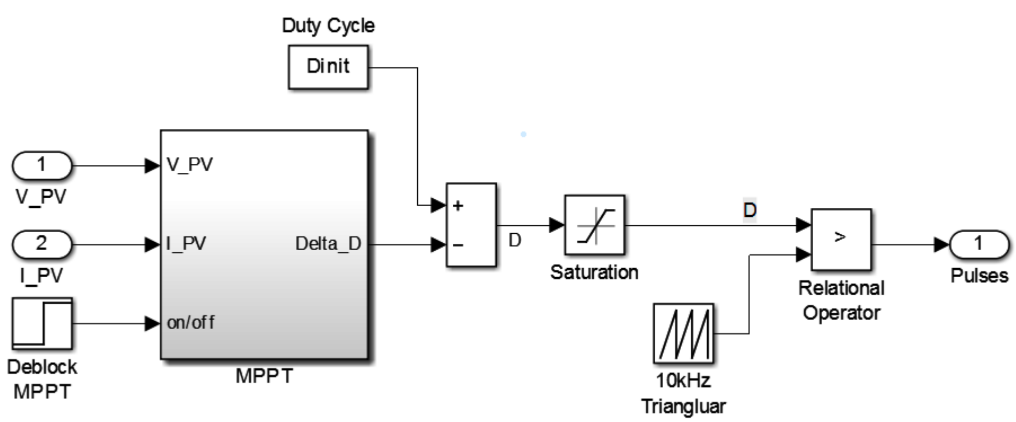

Fig. 6.7 Incremental conductance and Integral regulator method of MPPT-1

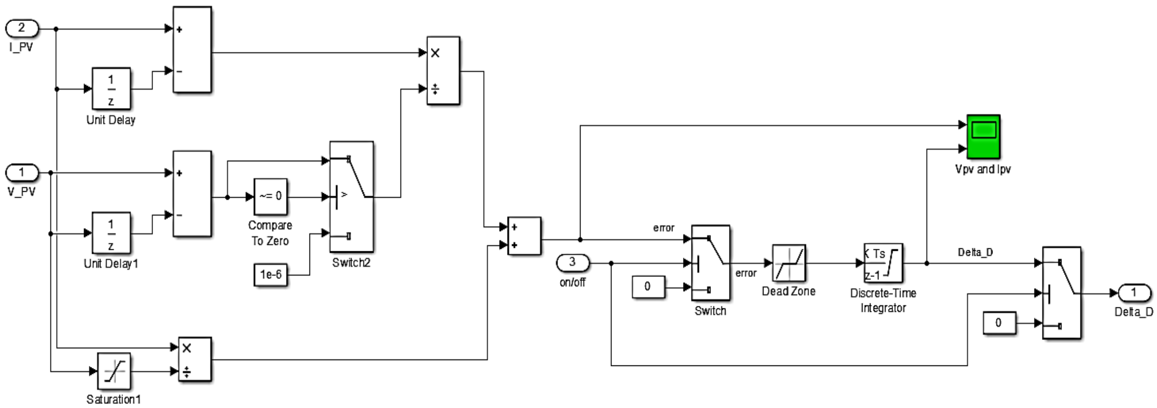

Fig. 6.8 Incremental conductance and Integral regulator method of MPPT-2

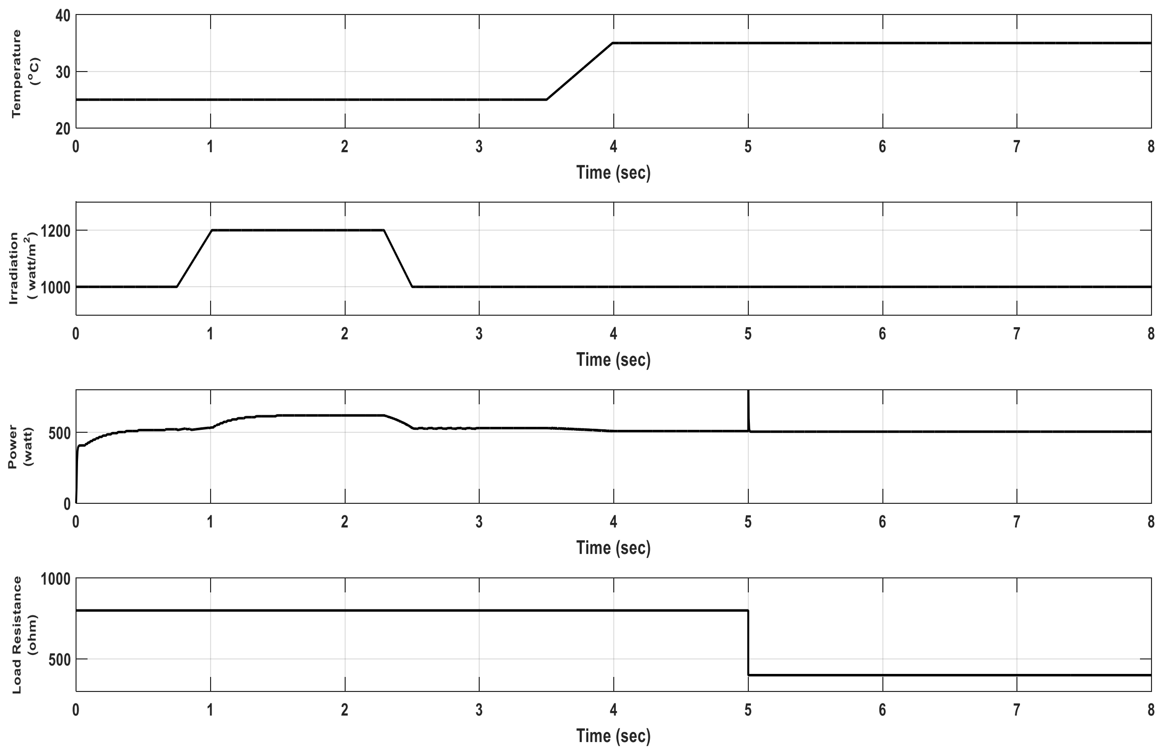

Fig. 6.9 MPPT output for changing Irradiance, Temperature and Load

6.4 Inverter Filter and complete system

Here unipolar modulation is used to invert the DC input and low pass, second order filter is used to get fundamental frequency output. Unipolar modulation has the advantage of low size filter than bipolar modulation because order of lowest dominant frequency is higher in unipolar modulation. The design of filter is carried out with the equation described in previous chapter. The following values are calculated for Low pass, second order LC filter.

L = 2.8mH, C = 100uF

DC load is also connected to the output of the boost converter. The dc supply is regulated to 220 Volt dc. Both DC and AC supplies is available from the developed system. In the proposed system dc load is 80 watt and ac load is 430 watt. Maximum power obtained from the panel is 540 watt. Thus the efficiency of the system is above 90%. Here results of AC load, DC load and panel output voltage and current are shown below. Now a inverter is connected with solar PV. But radiation continuously changes so to get the desired output in load side close loop control is applied. Modulation index is controlled to get the 230V output voltage.

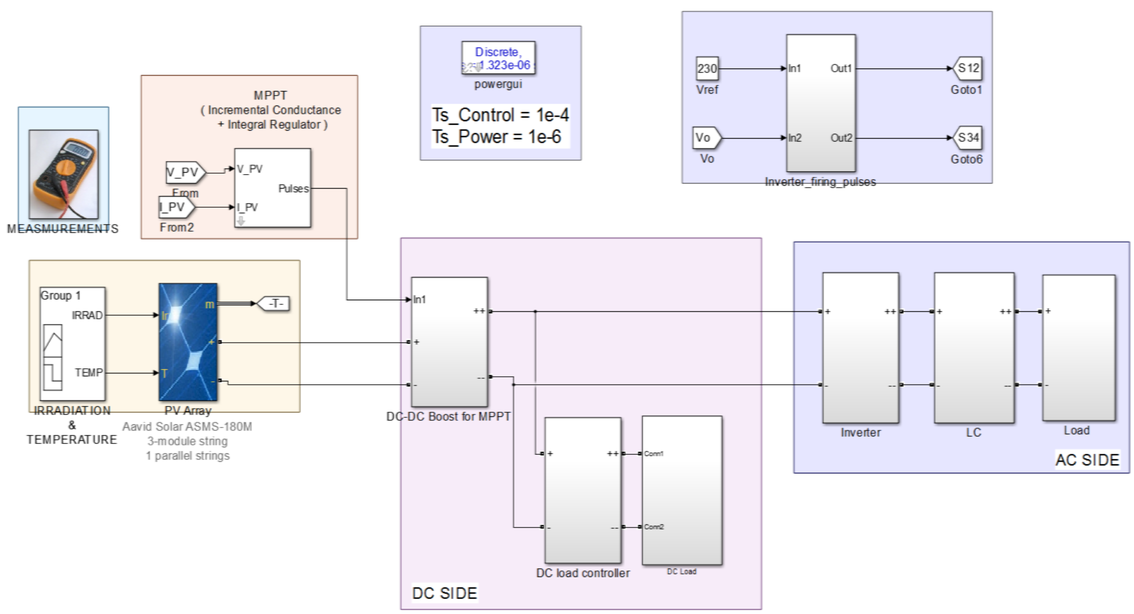

Fig. 6.10 MATLAB model of complete system

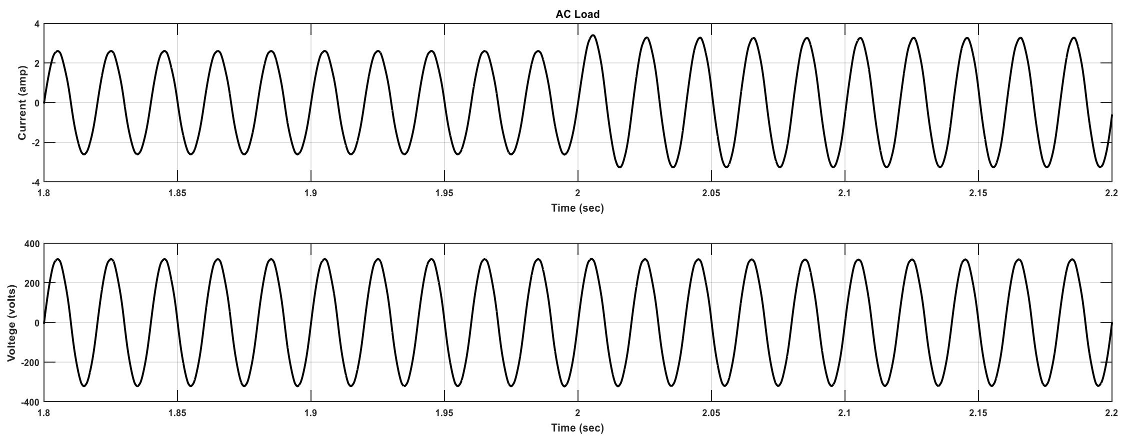

Fig. 6.11 Output of AC side voltage and current for variable load

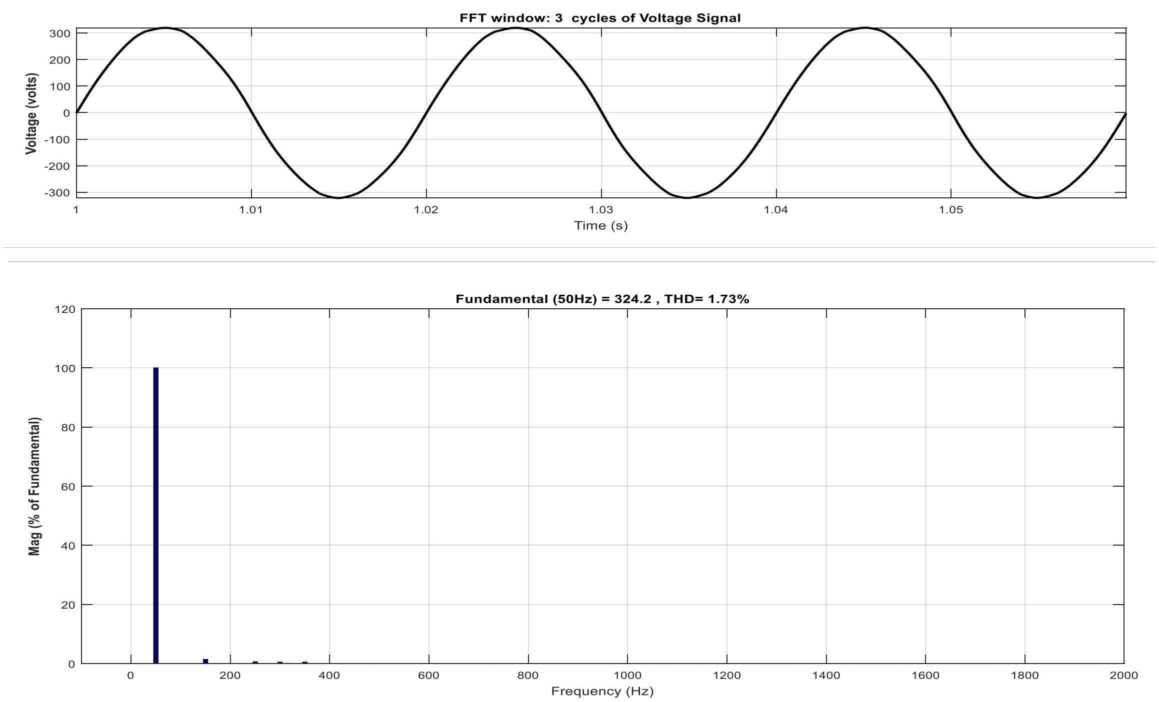

Fig. 6.12 Inverter output Voltage Fourier analysis

Switching frequency used is 20000 Hz. Modulation index is 0.82 for open loop system. Here RMS value of output voltage is 230V and THD is **1.73%** which is under standard.

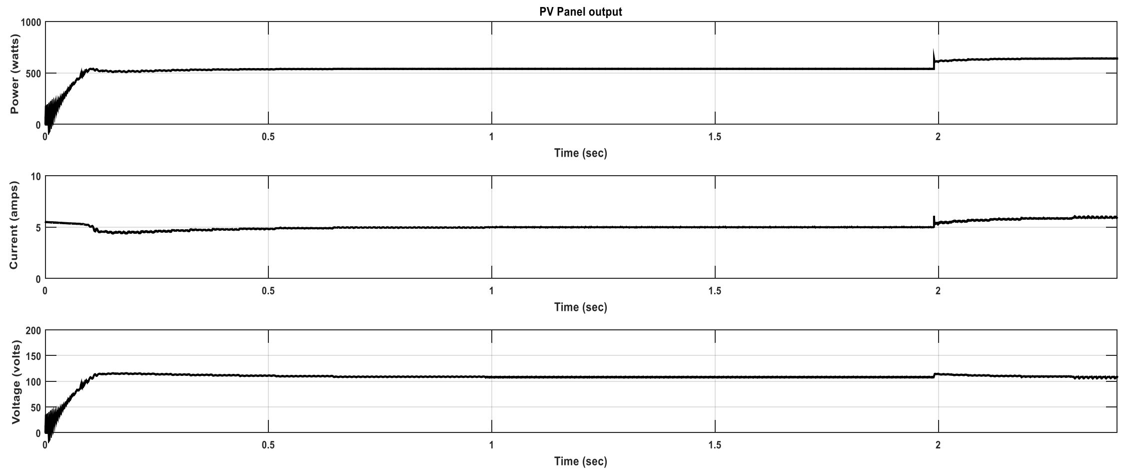

Fig. 6.13 Output voltage current and power of PV panel

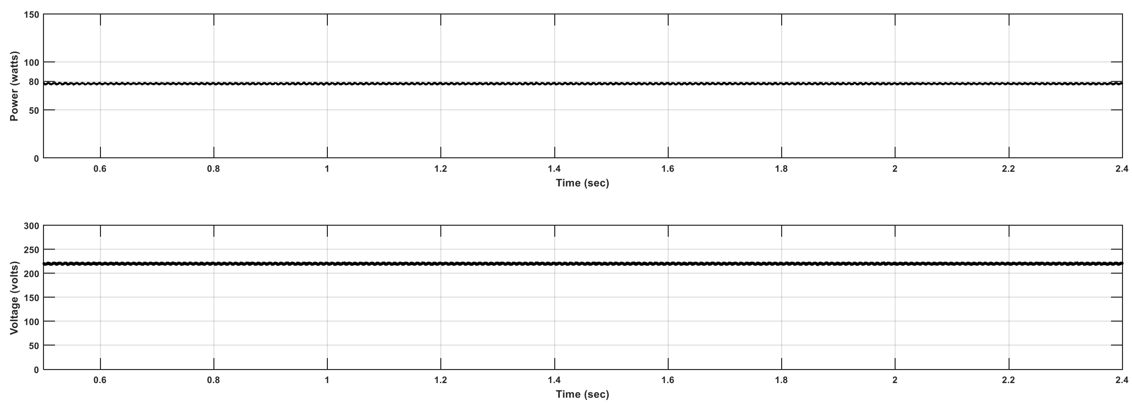

Fig. 6.14 DC load voltage and power

In complete system when there is irradiation change output voltage of DC-DC converter changes. So to get fix value of load voltage one need to control modulation index of inverter. Sometimes input voltage of inverter is not sufficient to make output 230 voltage. Then in this case Vdc control is done. By comparing output of boost converter to constant voltage and generation current reference with this.

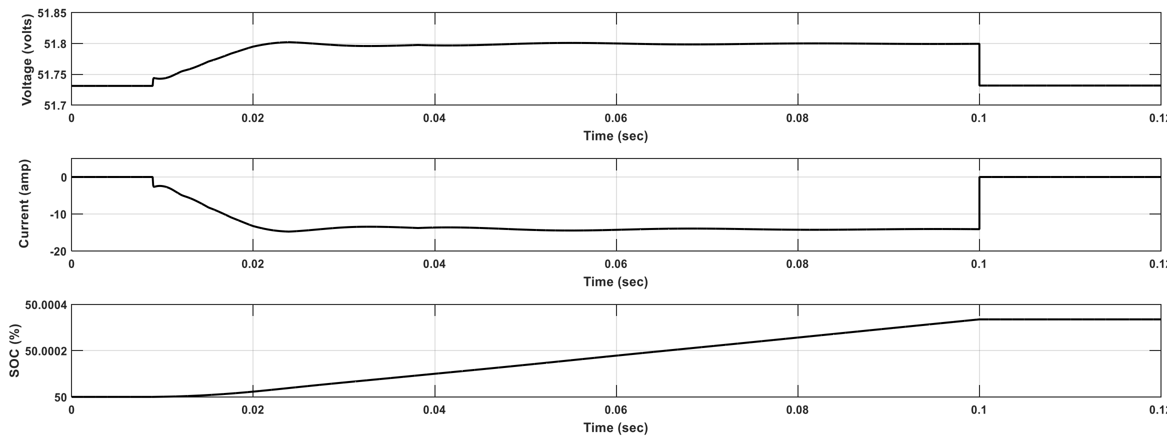

Fig. 6.15 Battery terminal voltage and current

To charge battery a charge controller is developed which charges battery with constant current and constant voltage method.

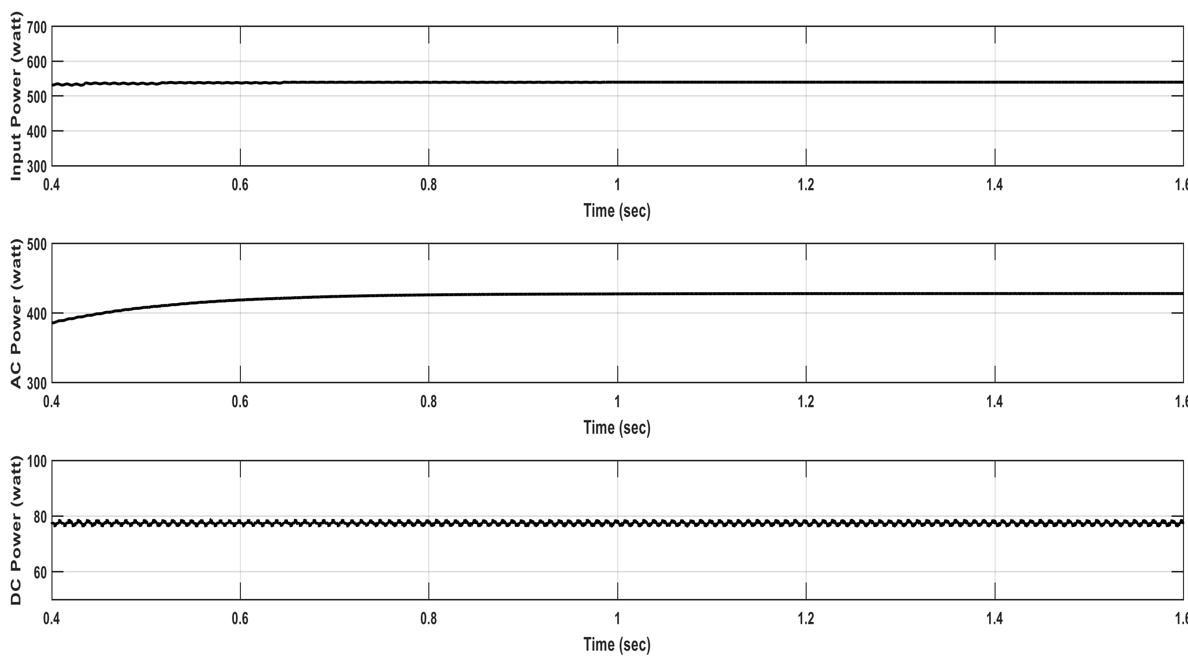

Fig. 6.16 Power Balance among solar, AC and DC loads

CHAPTER 7

HARDWARE IMPLEMENTATION AND FPGA CONTROLLER

7.1 INTRODUCTION

This chapter includes hardware implementation of the MOSFET driver circuit, boost converter, voltage sensor, current sensor and DC to AC inverter. Xilinx Spartan-3E FPGA controller is used for generation of firing pulses, analog to digital conversion and close loop control. Boost converter circuit is also developed for the purpose of maximum power point tracking for solar panels.

7.2 POWER CIRCUIT DEVELOPMENT

The following hardware circuit is developed,

- MOSFET gate driver circuit and snubber circuit
- Current and voltage sensor
- Regulated power supplies of +15,-15,+12,-12,+5,-5 volts

7.2.1 MOSFET gate driver circuit

7.2.1.1 MOSFET Specifications:-

- MOSFET – IRFP 460 (500v, 20A)
- Drain to source voltage (V_{dss}) = 500v
- Source to drain resistance during on period ($R_{DS(on)}$) = 0.27Ω
- Rated drain current (I_D) = 20A

Each MOSFET switch consists of an inbuilt anti-parallel freewheeling diode. No forced commutation circuits are required for the MOSFET's because they are self-commutated devices. MOSFET turn on when the gate signal is high and turn off when the gate signal is low. The load inductance restricts di/dt through MOSFETS; hence turn off snubber is required for protection. RCD turn off circuit is connected to protect the switch against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor).

7.2.1.2 Snubber Circuit (Protection of MOSFETS)

For low power handling circuit RC snubber circuit has been used for protection of main switching device. Switching high current in short time gives rise to voltage transients that could exceed the rating of the MOSFET. Snubbers are therefore needed to protect the switch from transients. Snubber circuit for MOSFET is shown in Fig.9.2. The diode prevents the discharging of the capacitor via the switching device, which could damage the device due to large discharge current. An additional protective metal oxide varistor (MOV) is used across each device to protect against over voltage across the device.

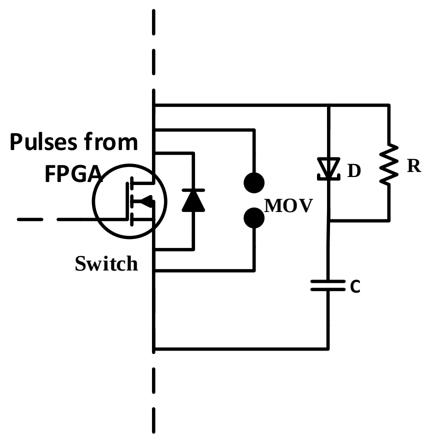

Fig. 7.1 Snubber circuit for MOSFET protection

<u>Snubber Components</u>

- Capacitance : 0.1µF,1000v
- MOV (Metal oxide Varistor): 320v
- Diode- IN5408
- Capacitor, C = 0.1µF, Resistor, R= 0.1kΩ, 5w

7.2.1.3 Driver Circuit (Pulse Amplification and Isolator)

The pulse amplification circuit for MOSFET is shown in figure 9.3. The opto coupler HCPL-3101 provides necessary isolation between the low voltage pulse circuit and high voltage power circuit. The pulse amplification circuit is provided by the amplifier transistor 2N2222. When the input gating is +3.3v level, the transistor saturates , the LED conducts and the light emitted by it falls on the base of the phototransistor, thus forming its base drive. The output transistor thus receives no base drive and remains in the cut-off state and a +12v pulse (amplified) appears at its collector terminal.

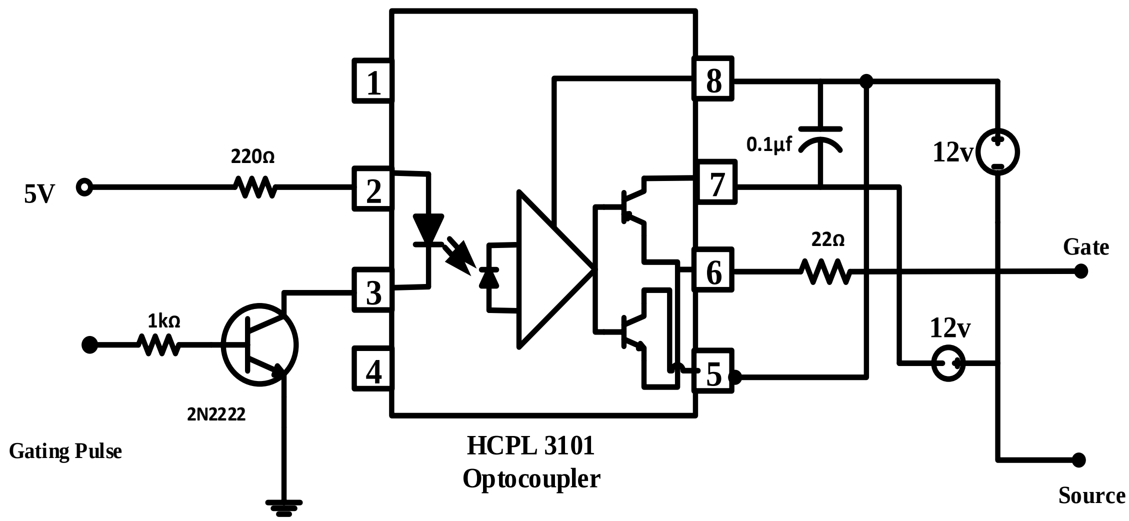

Fig. 7.2 FPGA pulse amplification and isolation

Fig. 9.2 and Fig 9.3 together makes the complete driver circuit for the MOSFET. Pulse amplification is required to meet the minimum gate current demand for the MOSFET to turn on and snubber circuit is required for the protection of MOSFET during abnormal conditions.

7.2.2 Power Supplies

DC regulated supplies (+15V, -15V, +12V, -12V and +5v) are required for providing biasing to various circuits like pulse amplification and isolation circuits, hysteresis controller and voltage detectors etc. using regulator IC's 7815, 7915, 7812, 7912 and 7805 for +15V, -15V, +12V, -12V and +5v respectively.

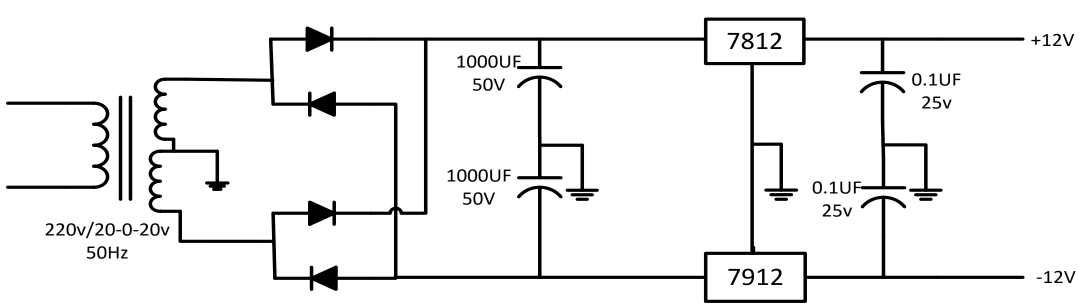

Fig. 7.3 +12V, 0, -12V supply

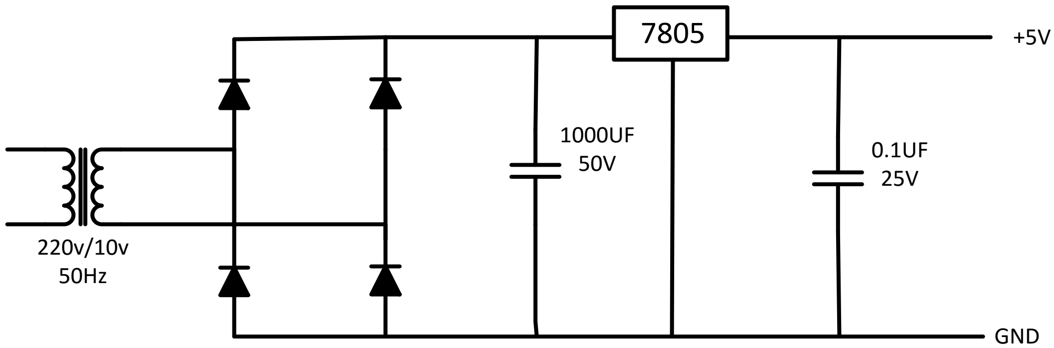

Fig 7.4 +5 volts supply

Circuit shows in fig. 9.5 gives output voltage of +12v and -12V. Similarly 7812 and 7912 is replaces by 7815 and 7915 to get +15V and -15V voltage supplies.

7.2.3 Current and Voltage Sensor

7.2.3.1 Current Sensor

For measuring various circuits current for controlling purpose Hall Effect current sensors (HTP 25) are used. The circuit diagram of the Hall Effect current sensor along with a buffer and a scalar circuit is shown in Fig.9.6. Here a current of I (A) in power network is converted into ±3.3V range. These current sensors provide galvanic isolation between power circuit and control circuit and requires a nominal supply voltage of the ±12V to ±15V. The voltage input to the buffer circuit is calculated by the equation $v_{oi} = R_o \left(\frac{N_p i}{c r_i}\right)$. Thus the voltage v_{oi} is scaled properly with the scalar circuit. The output voltage is given to the FPGA kit with the help of on board ADC and level shifter circuit. This level shifting is necessary in case of AC current sensing only because FPGA does not accept negative analog values. For pre amplifying gain setting of -1 in FPGA Spartan 3E board range of input voltage accepted is 0.4 volts to 2.9 volts. But in case of DC measurement no level shifting is required.

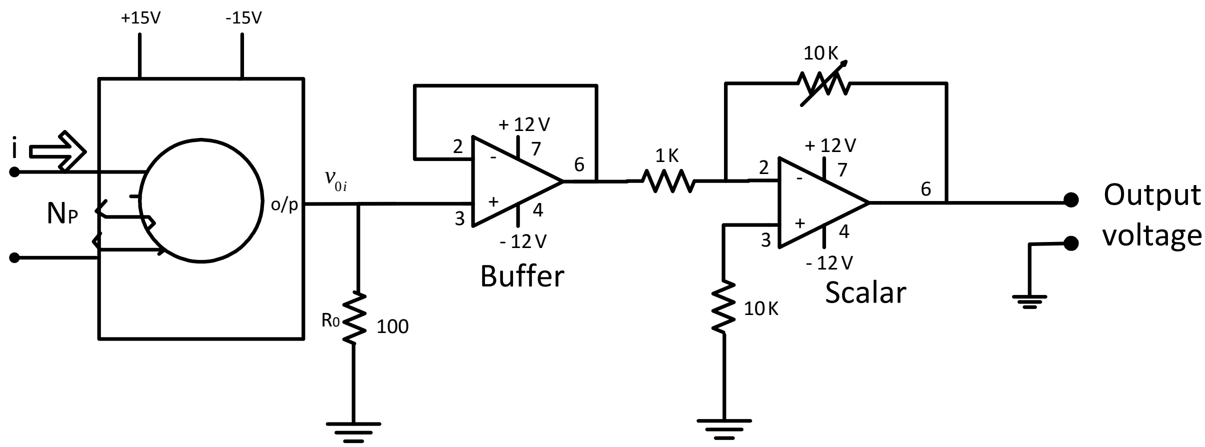

Fig.7.5 Current sensor circuit

7.2.3.2 Voltage Sensor

The circuit diagram of the sensing voltage along with the buffer and scalar circuit is shown in the following figure. The AD202JN is an isolation amplifier in the present experimental setup the power circuit voltage which is in the range of ±500 V is converted into ±5V range. The voltage at the output of the isolation amplifier is $v_{ov} = v_1 \left(\frac{R_2}{R_1 + R_2}\right)$. Thus the output voltage v_{ov} is properly scaled by a scalar circuit and the output voltage is given to the ADC of FPGA kit.

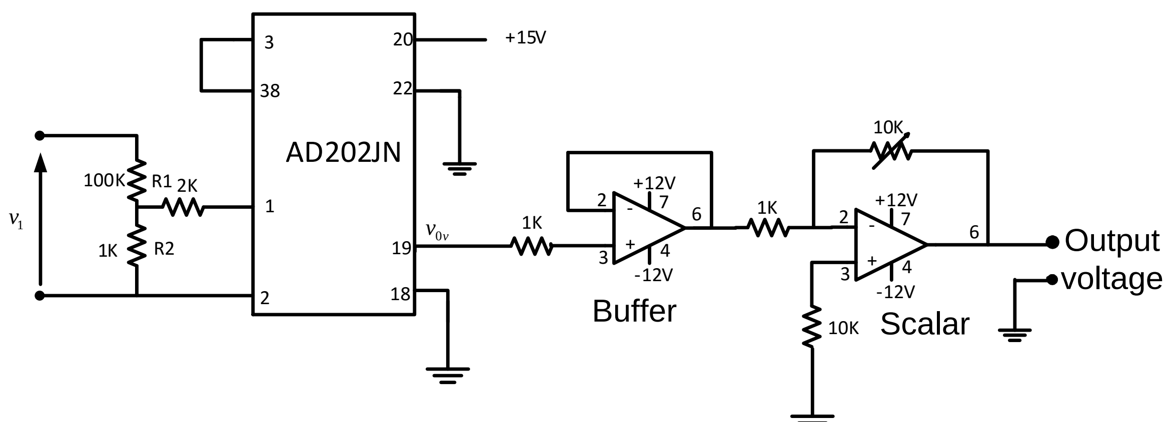

Fig.7.6 Voltage sensing circuit

7.2.4 Voltage source inverter circuit

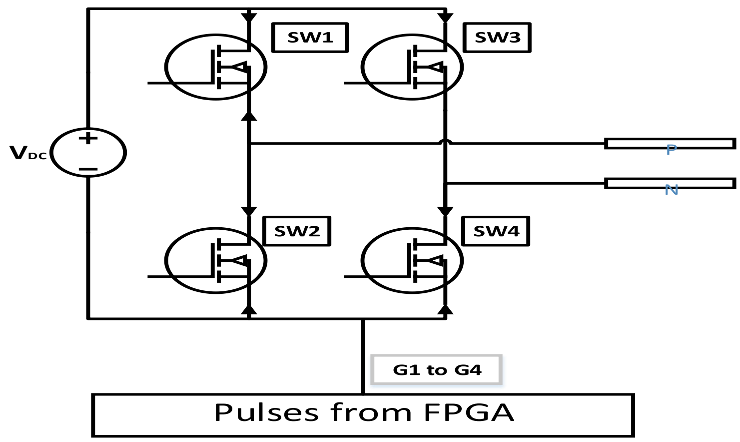

Fig. 7.7 Single phase inverter

7.3 FPGA CONTROLLER

FPGA stands for Field Programming Gate Array. Various companies produces FPGA. For this project Xilinx's Spartan-3E kit is used. Programming language used in FPGA is Verilog and VHDL. Here VHDL is used. It stands for Very large scale integrated circuits Hardware Description Language. To write code ISE (integrated software development) design suite 14.7 software is used. Unlike another controller FPGA uses HDL which describe the hardware on the board. Other controller like DSP or Arduino runs on a lines of code sequentially. FPGA can also run code sequentially like other controller. In VHDL various processes runs in parallel. FPGA first describes hardware itself and then their interconnection to produce output. Top level design approach is used to interconnect various parallel processes. There are around 10,000 of programmable gate on board. Some key component and feature of Xilinx XC3S500E Spartan-3E are:-

- 50 MHz on board clock oscillator.
- Two-input, SPI-based Analog to Digital Converter (ADC) with programmable-gain pre-amplifier.
- Eight Discrete LEDs.
- 2-line, 16-character LCD screen
- Xilinx 4 Mbit Platform Flash configuration PROM

- 64 MByte (512 Mbit) of DDR SDRAM, x16 data interface, 100+ MHz

A 50 MHz on board oscillator can be used to generate algorithm for various tasks. Generally a count variable is used for time related logic and providing delay in circuits. Xilinx ISE provide another tool iSIM simulator to view simulation results before loading the code to board. Once code has been written we should check its behavior in iSIM simulator. To connect various pins on board with each other user constraint file (.ucf) is written. Before downloading the code onto the board following 3 steps are to be successfully completed to avoid syntax and logical errors:-

1. Synthesize-XST
2. Implement design (includes Translate, Map and Place and route)
3. Generate programming file

On completion of these steps a .bit file is generated. ISE provide another tool iMPACT to download the .bit file onto the board. The code is on board till supply is switch on as program is written on RAM.

7.3.1 Generation of SPWM using FPGA

To generate SPWM using FPGA look up table method is used. In FPGA various process can run in parallel. Following steps are followed to generate SPWM:-

- Generate data of sinusoidal and triangular waveforms for one cycle. MATALB can be used to generate dataset.
- Using on board 50 MHz clock and count variable generate waveform of proper frequency form two different processes.
- Compare data to sine and triangular waves using another process triggered by sine and triangular data.
- Provide proper dead between pulses of two legs to avoid short circuiting of DC supply band (2-5 us).
- Simulate the model in iSIM simulator and check the results.
- Write .ucf file and upload the code onto board using iMPACT.

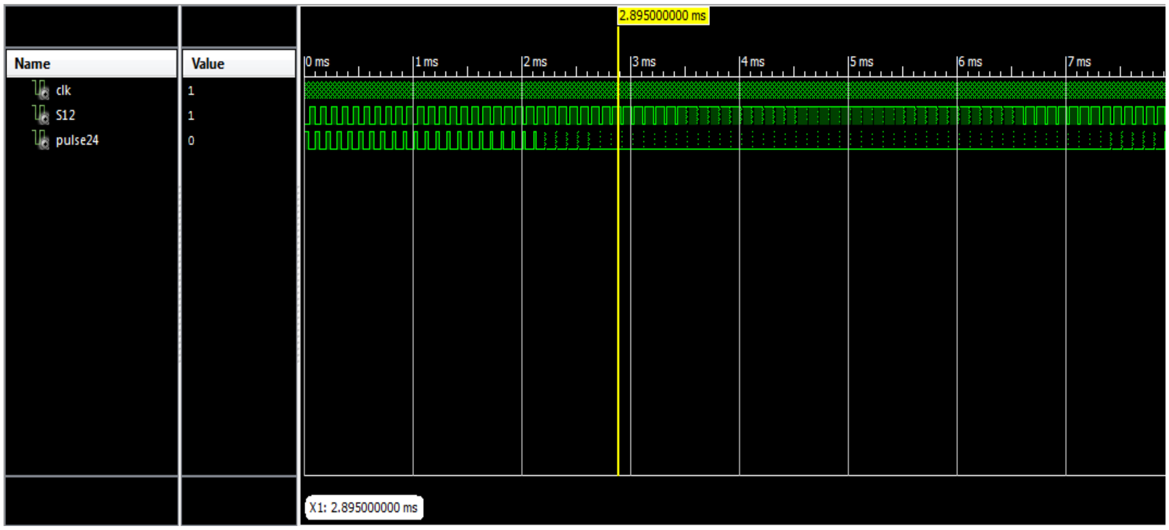

Fig. 7.8 SPWM pulses view on iSIM simulator tool of ISE 14.7 with 5 us dead band

7.4 HARDWARE SET UP AND RESULTS

For hardware a boost converter in cascaded with single phase inverter is made. Pulses are generated from FPGA board. For boost 10 kHz pulses are generated with 0.4 duty ratio. Inverter pulses for output frequency of 50 Hz and triangular frequency of 10 kHz and bipolar modulation are given.

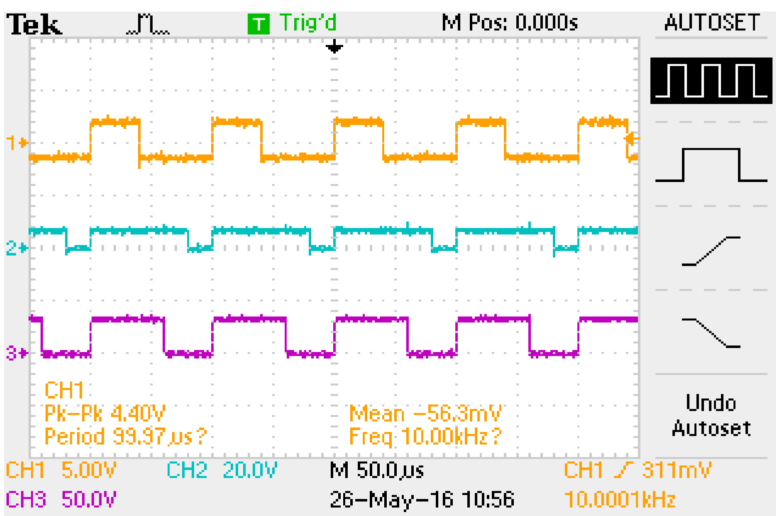

Fig. 7.9 Pulses from FPGA controller for boost converter with d = 0.4, 0.6, 0.8

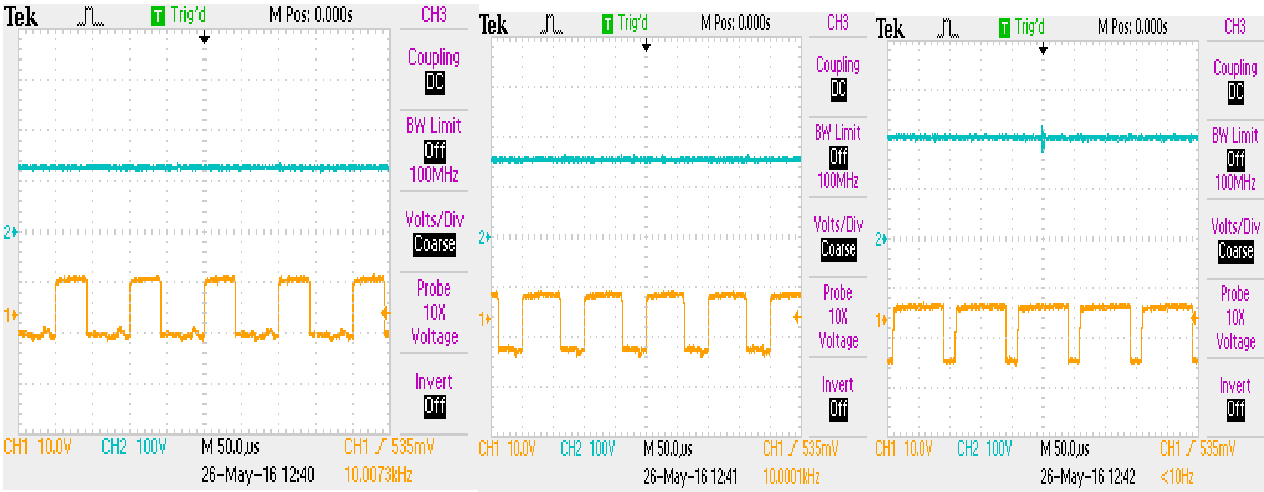

Fig. 7.10 Boost output comparison for Vin = 20V and d = 0.4, 0.6, 0.8

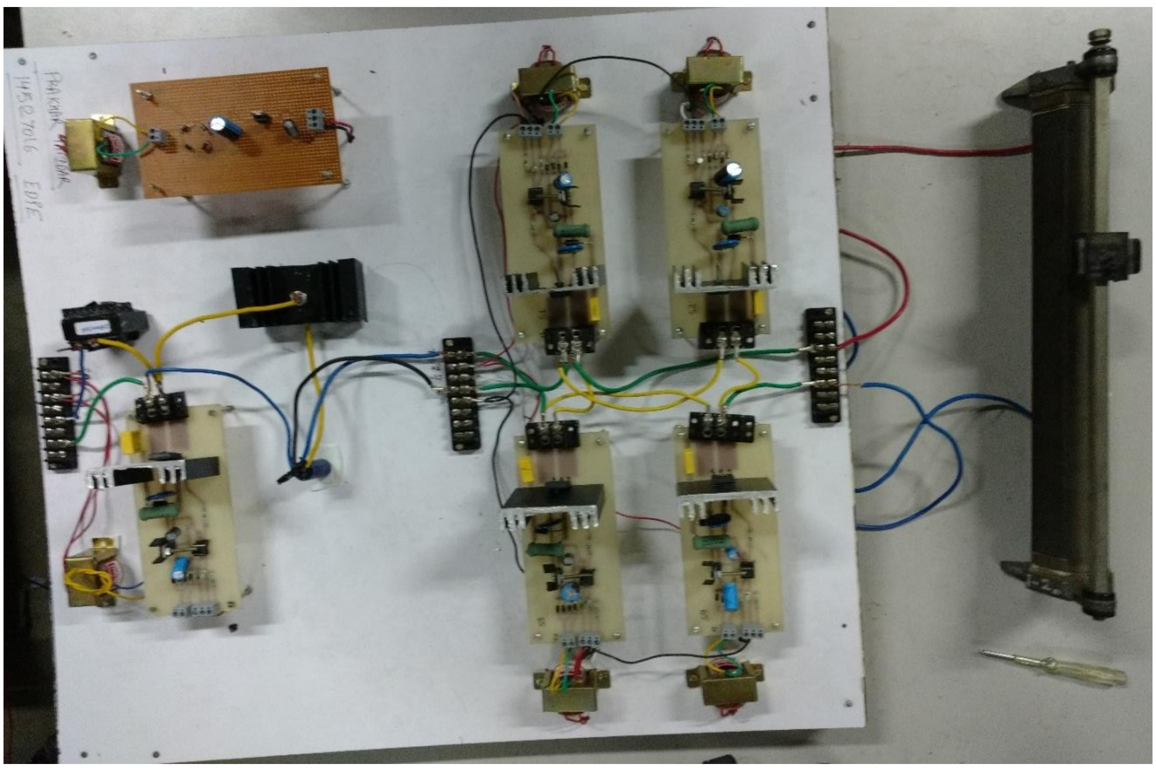

Fig. 7.11 Boost converter cascaded with single phase inverter

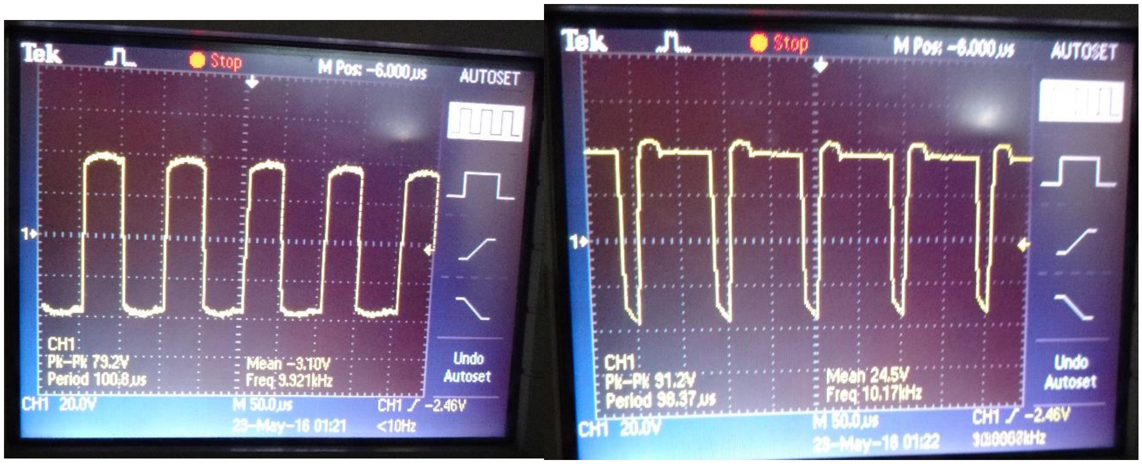

Fig. 7.10 Output of Boost and inverter

7.4 CONCLUSION

In this chapter a boost converter is presented in cascaded with single phase inverter. FPGA has a very large control possibility. We can use ADC available with SPARTAN-3E kit. It has 2 board.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

In dissertation work rooftop solar system has been well developed and simulated using MATLAB sim power system toolbox. Their results has been shown in chapter 7. This thesis investigates about using solar energy for Dc as well AC loads. Maximum power extracted form solar panels divides in DC loads, AC loads and remaining power fed to batteries. If there is power deficiency battery supplies that amount of power.

Grid connection is being popular with solar. Various single stage topologies are available for grid integration. For standalone battery charging and discharging can be better designed. Close loop control for the hardware system can be developed.

Fast MPPT techniques like neural networks and fuzzy logic can be used to track maximum power point of solar arrays. Boost converter model transfer function is verified using Simulink MATALB. For more accurate model parasitic resistance of capacitor and inductor should take into account. This accurate model provide more accurate PI parameters.

Vdc control is another method to control the output voltage of boost converter before being feed to inverter. While synchronizing with grid system must be able to disconnect itself in case of fault occurs. Inverter must be anti-islanding protected before connected to grid.

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APPENDIX

Battery charging algorithm

```
function [Vref,Iref,signal,SD] = CHARGER(V,I,T)
persistent temp_i temp_v temp_signal temp_fault CC CV n ;
if isempty(temp_i)
   temp_i=0.2;
end
if isempty(temp_v)
   temp_v=0;
end
if isempty(temp_signal)
   temp_signal=1;
end
if isempty(temp_fault)
   temp_fault=1;
end
if isempty(CC)
   CC=1;
end
if isempty(CV)
   CV=0;
end
if isempty(n)
   n=0;
end
if (T>n*0.02) % sample time is 0.02s
   n=n+1;
   if CC
      if V<58.4
         temp_i=0.1;
         temp_v=0;
         temp_signal=1;
      else
         CV=1;
      end
   end
   if CV
      if I>5.0
         temp_i=0;
         temp_v=1;
         temp_signal=2;
      else
         temp_fault=0;
      end
   end
```

```
    if I > 20
        temp_fault = 0;
    end
end
signal=temp_signal;
SD=temp_fault;
Iref=temp_i;
Vref=temp_v;
end
```

2. TRANSFER FUNCTION OF BOOST CONVERTER

```
% Model for a non-isolated Boost dc-dc converter

clc

%% Initalize the plant parameters

disp('The values of the plant parameter');
Vg=108; % Input voltage
D=0.73; % Steady state duty ratio
L=0.59e-3; % Inductance
C=9.22e-6; % Capacitance
R=296.2; % Ohms

%% Steady state model of Boost converter

%given by As, Bs, Cs, Ds
As=[0 -(1-D)/L ; (1-D)/C -1/(R*C)];
Bs=[1/L 0 0; 0 -1/C 0];
Cs=[0 1; 1 0];
Ds=[0 0 0;0 0 0];

Vo= -Cs(1,:)*inv(As)*Bs(:,1)*Vg;
Ig= -Cs(2,:)*inv(As)*Bs(:,1)*Vg;

%% Small signal model of Boost conveter
% for controller design purpose
% can be modelled for only the desired outpur control
%given by a,b,c,d

a=[0 -(1-D)/L ; (1-D)/C -1/(R*C)];
b=[1/L 0 Vo/L; 0 -1/C -Ig/C];
```

```
c=[0 1];
d=[ 0 0 0 ];
ulabels=['vg iz d'];
ylabels=['vo ig'];
xlabels=['il vc'];
printsys(As,Bs,Cs,Ds,ulabels,ylabels,xlabels)
printsys(a,b,c,d,ulabels,ylabels,xlabels)

%% Transfer function of the system
% vo/d
disp('Transfer function in s-domain');
disp('vo/d (s)');
TFB=zpk(tf(ss(a,b(:,3),c,[0])))
pidTuner(TFB);
rlocus(TFB);
% It has one zero in right hand side of s-domain so bode plot can not be used. we use root
locus technique to design of controller.

%% Transfer function of the system
% Vo/D(s)
disp('Vo/Vi');
tfb11 = zpk(tf(ss(As,Bs(:,1),Cs(1,:),[0])))
```