

DESIGN AND IMPLEMENTATION OF PHOTO VOLTAIC EMULATOR

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEM

Submitted by

Hari Charan Verma

2K13/PSY/07

Under the supervision of

Dr. Mukhtiar Singh
(Associate Professor)



DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

2015

CERTIFICATE

I, HARI CHARAN VERMA, Roll No. 2K13/PSY/07 student of M. Tech. (Power System), hereby declare that the dissertation titled “DESIGN AND IMPLEMENTATION OF PHOTO VOLTAIC EMULATOR” under the supervision of DR. MUKHTIAR SINGH of Electrical Engineering Department, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi
Date: 08/07/2015

HARI CHARAN VERMA
2K13/PSY/07
M.Tech (PS)

DR. MUKHTIAR SINGH
Associate Professor
EE Dept., DTU

CANDIDATE DECLARATION

I, Hari Charan Verma, Roll No.-2K13/PSY/07 student of M. Tech. (POWER SYSTEM), hereby declare that the dissertation/project titled “**Design and implementation of photo voltaic Emulator**” under the supervision of Dr. Mukhtiar Singh, Department of Electrical Engineering, Delhi Technological University, in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi
Date: 08/07/2015

Hari Charan Verma
M.Tech (Power System)
2K13/PSY/07
Dept of Electrical Engineering
DTU, New Delhi

ACKNOWLEDGEMENT

I am indebted to my thesis supervisor **Dr.Mukhtiar Singh**, Department of Electrical Engineering, for her gracious encouragement and very valued constructive criticism that has driven me to carry the project successfully.

I am greatly thankful to **Prof.Madhusudhan Singh**, Head of Department, entire faculty and staff of Electrical Engineering Department and friends for their, continuous support, encouragement and inspiration in the execution of this “**thesis**” work.

Finally I express my deep sense of gratitude to my parents who bestowed upon me their grace and were source of my inspiration and encouragement.

Hari Charan Verma
M.Tech (Power
system)
2K13/PSY/07
Dept. of Electrical Engineering
DTU, New Delhi

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ABSTRACT

In the proposed work emulator of photovoltaic system have been developed. The main purpose of developing solar emulator is generate the profile of solar PV system from laboratory based experimental studies. The mathematical model of solar photovoltaic system is developed and simulated using the MATLAB. Here, the main aim is to generate VI Characteristics of PV system at different irradiation and temperature level. The actual data from NREL have been taken as reference to generate PV Characteristics from Real time irradiance level using lookup table. In this work, only One Diode equivalent model has been considered. The series or shunt connection of this system diode model is further used to immolate a solar array. The Newton Raphson Method has been used to calculate the output current of solar cell while taking temperature and irradiation level as input variable and voltage as output. Further a PIC 18F4520 microcontroller with flash memory of 32 kB is used to handle large data where the code written in C language is burned inside microcontroller to emulate to proposed PV system.

CHAPTER 1

INTRODUCTION

1.1 Requirement of PV Emulator:-

We have seen tremendous growth in Renewable energy sources mainly in photo voltaic system in past decade and also the installation of photovoltaic system has average annual growth rate of 110%. Increase in installation of photo voltaic system has caused many problem for photo-voltaic equipment manufacturers. Some issues in PV systems are voltage regulation, coordination with protection system and fault calculation of transient stability. Due to regular change of parameter of photo voltaic we can't test the photo voltaic equipment.

These days, Installation of PV system in India is increasing. Photo voltaic testing equipment like inverter, the inverter is directly connected to photo voltaic module with that problem arises in photo voltaic module which depends upon its initial parameters like temperature, irradiation causing electric characteristics to change. Due to changing of output of PV module makes it difficult to isolate the variable affecting PV module. If we use the programmable power supply then output of PV current and voltage are static that do not change and if we required to change the output current and voltage then we have to change the program. A photo voltaic Emulator is a perfect medium between a real photo voltaic module and a programmable power supply. PV emulator gives more accurate output compare to programmable power supply with real environment condition so we test the PV hardware.

Photo voltaic has good marketing scope these days, manufacturers are facing lots of challenges to test the grid connected systems. Grid connected power system in India is 3744 MW at end of March 2015 and it is expected to have additional 10,000MW power at the end of 2017 and also expected that total power capacity will be about 100,000 MW by 2022. **4-7kwh/m²** of average solar energy incidences daily over the surface of India. Government of India started Jawaharlal Nehru national solar mission in 2010 to promote the solar energy generation in India.

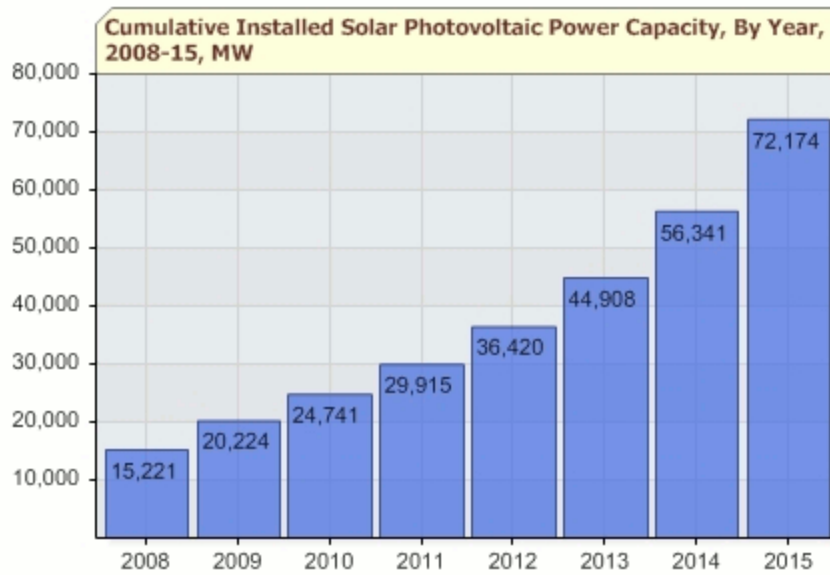


Fig1.1:-solar photovoltaic power capacity

It is very difficult to test photovoltaic equipment as external environmental condition is changing regularly. Inside the PV emulator user can specify the panel type, irradiance and temperature. For example, to determine how the PV system will react to a Sunpower 205-BLK module at an irradiance of 500W/m² at 20°C, the user will specify these parameters to the PV emulator. We can vary either the irradiance or temperature and can find out how these parameters affect the PV hardware being tested. Consistent electrical characteristics will allow the analysis and optimization of PV systems. The increased control that a PV emulator provides allows for more sophisticated measurements of maximum power point tracking (MPPT) algorithms of inverters, as well as their total harmonic distortion (THD) and power factor (PF) control under various conditions. For grid connection testing, we required more than hundred solar panels that will be more costly for purchase for only testing purpose. So a P V emulator would be simulate many solar panels by changing the program with various temperature and environmental condition. We only change the type of solar panel in programming and we use new P V panel and connect to P V hardware to be tested.

1.2 Applications:-

Different types of P V Emulators have been implemented over the years. To emulate the solar panel, different hardware has been developed and also different control strategies have been used. By using specified P V cell parameters, most of P V emulator take a mathematical model and find the output voltage and current characteristics based on specified parameter of this device. Mathematical model allows the MATLAB simulation or MATLAB program of solar panel under different temperature and irradiation.

In previous few year, control system used for implementation of P V emulator is DSP board based on loop up table, use of op-amps and digital system. Some developer has used single reference solar cell and a current amplifier to develop the P V panel module. Some method also implemented by this used loop up table where current & voltage discrete value of solar panel are stored and then using linearly interpolated control strategy for photo voltaic emulator. In this thesis, I used microcontroller based control strategy.

PV emulators are developed for different purposes like education, industries and research. In space satellite, we test the photo voltaic system by using the PV emulator. Due to different condition in space, PV emulator developer can easily and quickly simulate the photo voltaic system. Only PV emulator is best choice for testing in space.

1.3 solar panel physics

By using the photo electric effect, photo voltaic cells produce electrical power. They convert light energy into electric energy. Solar cell is only a p-n diode and diode is composition of P type and N type semiconductor combined together, by using the doping concentration in P-N semiconductor we made a solar cell. There is a wide range of doping elements used to compose a solar cell. The choice of these doping elements affects how efficient the solar cell is at converting light energy into electrical energy. Conversion efficiency of light to electrical energy depends upon the doping elements. Also price of solar panel depends upon the doping elements used by the manufacture. Its cost of manufacturing depends on doping level elements.

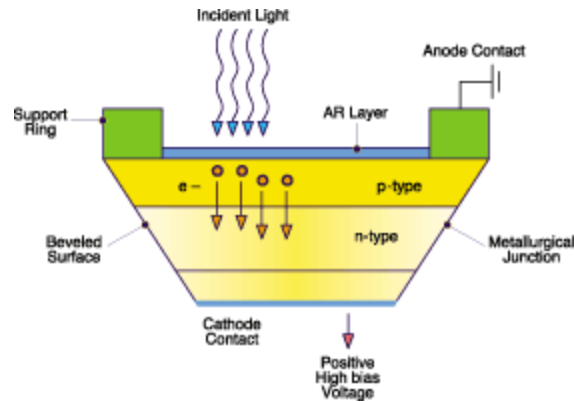


Fig1.2:- p v cell diagram

Solar cell is composition of semiconductor but in semiconductor, small band gap is available between valence band and conduction band. Photon has required some energy to jump from conduction to valence band. A photon energy larger then gap energy then remove the electron from solar cell and electric current produces.

$$\text{Required photon energy} = hc/\lambda.$$

Where $c = 3 \times 10^8$ m/s

$$h = 0.626068 \times 10^{-34} \text{ m}^2 \text{ kg/s}$$

if band gap is large then large photon energy required to pass from conduction band to valence band also efficiency of solar cell depends on band gap.

Diode Ideality Factor (n) and Band Gap Voltage (Eg)		
Cell Type	n	Eg
Mono-Si	1.026	1.12
Poly-Si	1.025	1.14
a-Si:H	1.8	1.65
a-Si:H tandem	3.3	2.9
a-Si:H triple	3.09	1.6
CdTe	1.5	1.48
CIS	1.5	1
AsGa	1.3	1.43

Table 1:-Band gap voltage and diode ideality factor

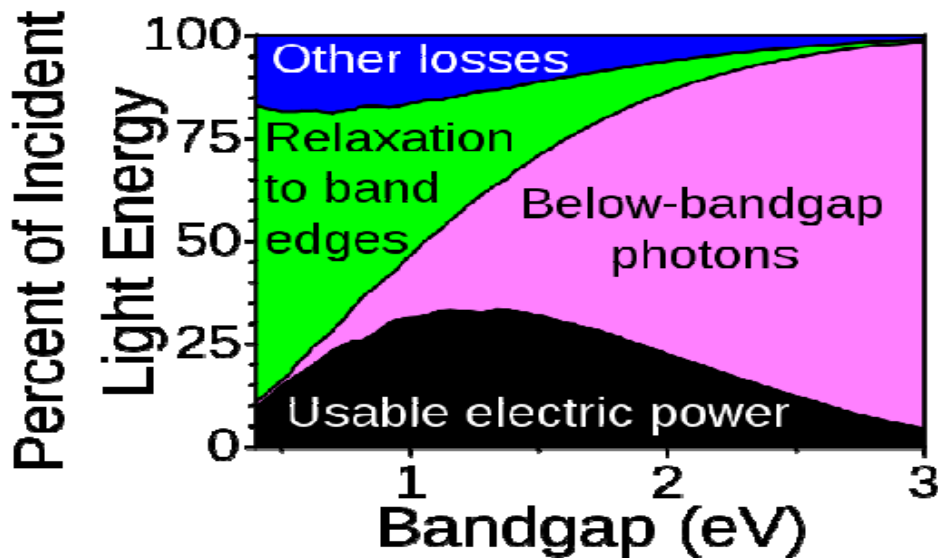


Fig1.3:- Shockly Queisser limit

Green portion produced due to relaxation of semiconductor electrons at band edges. When more energy of photon strikes to less band gap then remaining photon wasted at band edges. For example if 3ev energy of photon strikes to 1ev band gap then 2ev energy of photon wasted and accommodate at band edges. Blue portion of this curve shows, power losses occurs due to recombination of electron and hole. Pink portion of this curve shows power loss due to which photon that does not cross the band gap due to less energy. Photon power is wasted because it is not utilized for solar cell.

1.3.1 Irradiation Limit:-

Power generation of solar cell depends on two factors intensity of incoming light and wavelength of incoming light or rays. Each type of semiconductor has its capacity to absorb the intensity of light. Below that energy no intensity of ray absorb in semiconductor. The energy of semiconductor depends on the wavelength of the light. Solar cell designed best on spectrum portion. Light intensity increase than conduction of current increase due to large flow of photo electron emission semiconductor material. Large amount of visible spectrum portion is absorbed by solar cell which is about 390nm to 700nm and opposed to ultra violet light which is above 750nm and infrared light which is below 390nm.this portion is described in figure below

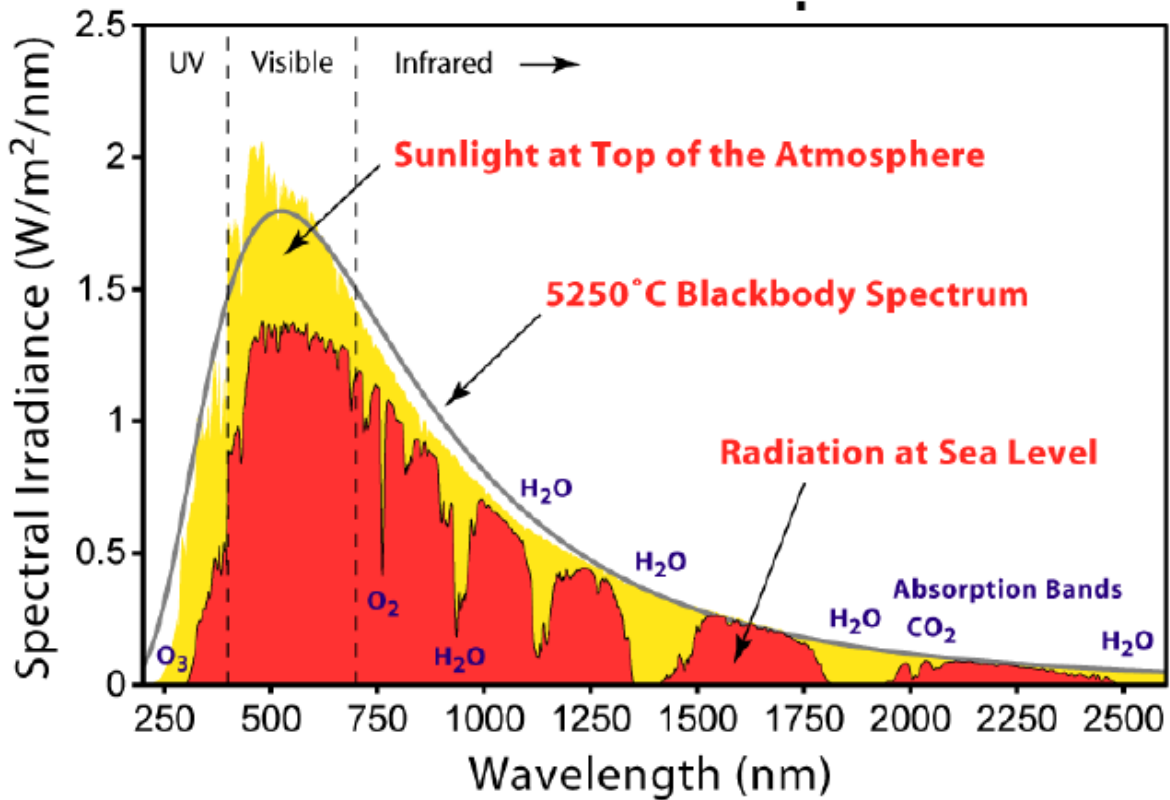


Fig1.4:- irradiation spectrum

1.3.2 Temperature Limit

Power is directly proportional to the irradiation of light and inversely proportional to the temperature. Solar cell works properly when voltage between solar is equal voltage of energy band gap .it occurs when temperature is 0 kelvin. If temperature increase then voltage across solar cell and voltage of energy band gap decrease so requirement of photon energy to jump conduction band decreases.so output current of solar cell increases but drastically the output voltage decreases. Overall output power of solar cell decreases. Therefore installation of solar panels are kept at cold climate region so solar panel absorbs more sun light at low temperature and produces overall large amount of power.

1.3.3 Semiconductor Limit:-

Photo voltaic solar panel depends on type of material used and material depends on the doping material and band gap of semiconductor. Shockley-Queisser limit describes the maximum efficiency of solar cell. Its graph shows behavior of maximum efficiency of solar cell with band gap of material.

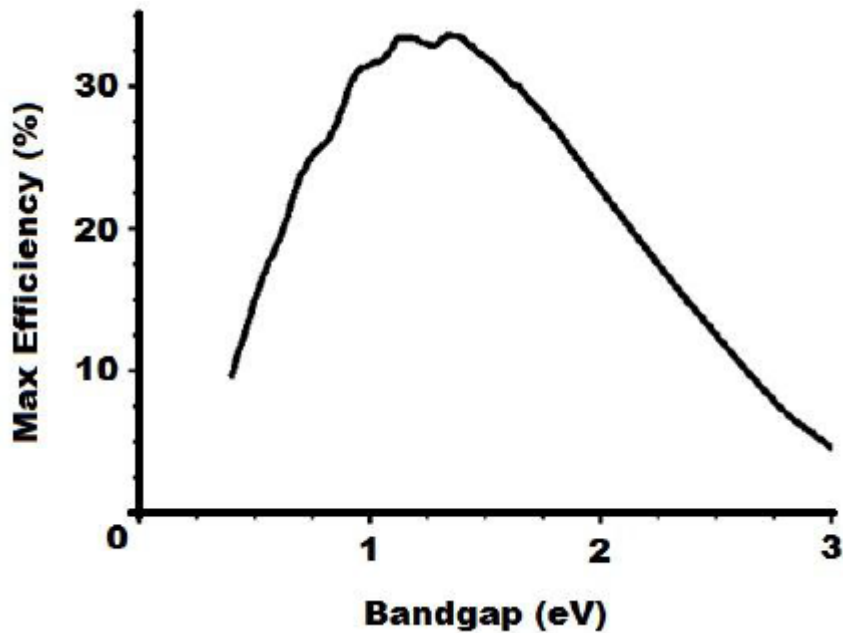


Fig1.5:- efficiency behavior of solar cell

1.3.4 Solar Panel Types

Several types of solar panel materials are available in market commonly used materials are Thin film, crystalline silicon type and multi junction type. Crystalline silicon type are also two types mono crystalline silicon and polycrystalline silicon. I explain below the advantages and disadvantages of that material. Each type of solar cell produces different V-I characteristics.

Mono crystalline Silicon: mono crystalline silicon is made based on highest purity, single thin wafer and single crystal rod. It is more expensive because it is made at single thin wafer. its structure sections are made up of crystalline silicon in one piece. This material tested in laboratory

then its efficiency is about 24% but when it is used in solar panels or practically then its efficiency is about 15%. This material is more costly, high weight. Large single thin wafer silicon crystal are rare in nature but also difficult to develop.

Polycrystalline Silicon: polycrystalline silicon is produced by multi silicon material in bars. It is also converted into single crystal bar. Polycrystalline silicon efficiency is about 19% when tested at laboratory but about 14% when used as solar panel. This material is pure, low cost and high profitable efficiency in comparison to mono crystalline silicon.

Thin-film Solar Cell: They are produced by placing thin layer about nanometer to tens of micrometer of a thin film photo voltaic material on wide range of surfaces. This material is low cost and less efficient to manufacture in comparison to both crystalline silicon types. By using this material roll type solar panels are made for eliminating the manufacturing cost in conventional panels. It is categorized like which photo material used.

Amorphous Silicon: This type of material is composition of hydrogen and silane gas vapor deposition. Deposition will be done at glass as well as plastic. By using deposition parameter, it can produce amorphous silicon, polycrystalline silicon and nanocrystalline silicon. If we use composition of polycrystalline silicon and nanocrystalline structure then it produces high value of open circuit voltage. This material can be deposited at low temperature about 75 degree Celsius. This material used solar panel when tested in laboratory then its efficiency is 13% and used in commercial purpose then its efficiency is about 8%.

Cadmium Telluride: for producing the photo voltaic solar cell we sandwiched cadmium sulphide and cadmium telluride. This material efficiency is about 16% when tested at laboratory but about 8%.

Copper Indium Diselenide: This material efficiency is about 17% when tested at laboratory but about 9%.

Dye-sensitized Solar Cell: It is the composition of titanium dioxide particle. it is more costly.

Gallium Arsenide: It is mixture of gallium and arsenic so this material is most efficient and its efficiency is more compare to other material. This material efficiency is about 25.7% when tested at laboratory but about 20%.

Multi-junction or Tandem Cells: In this material multiple p-n junctions are available. Each part of cell are constructed with different wavelength to reduce the losses and increase the efficiency. Currently, the silicon solar cells efficiency in laboratory is about 25%, while multi junction cells efficiency in laboratory is about 42%. This material is more expensive. This is used for space application or light concentrators.

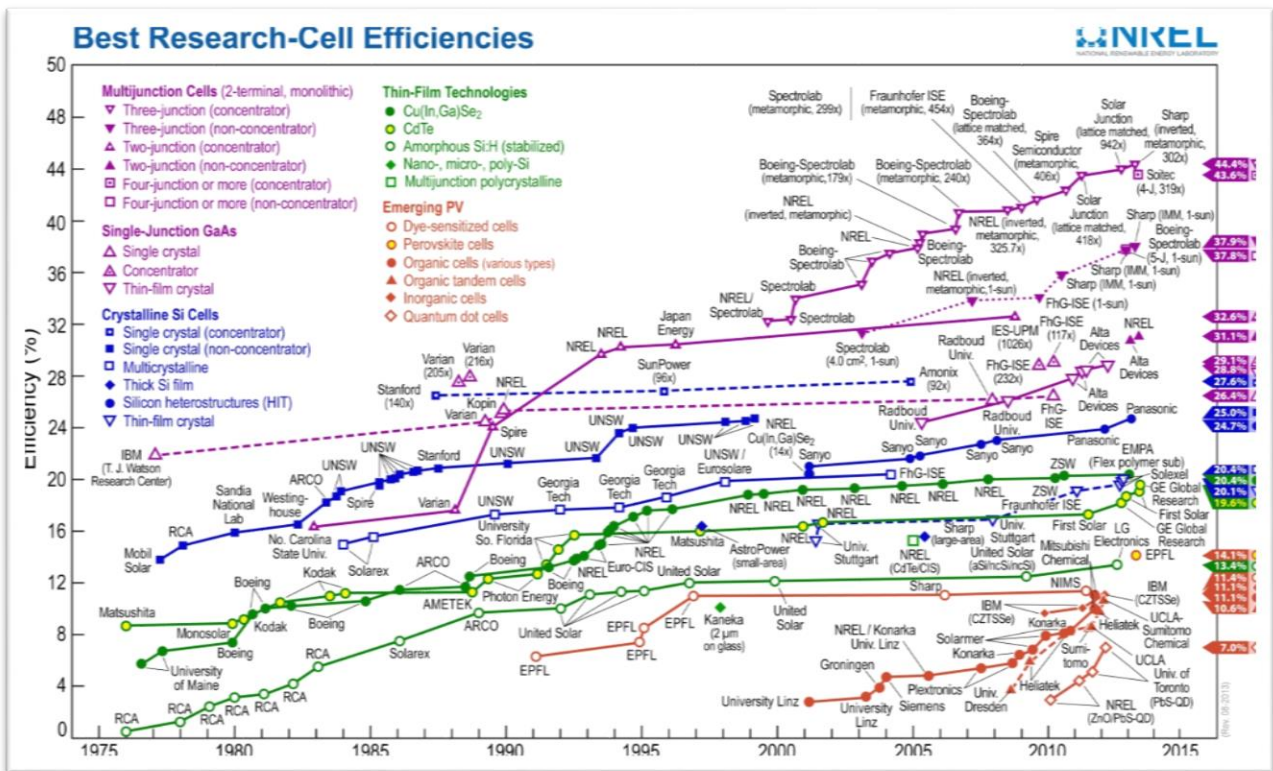


Fig1.6:- cell efficiency

CHAPTER 2

LITERATURE SURVEY

Guillermo martin segura and joaguim lopez mestre develop a photo voltaic emulator based on full bridge structure. Specification of the system is output voltage rating 0-650 V, output current rating 0-7 A and power rating 4.4KW. Guillermo martin segura used the microprocessor to control the converter actually microprocessor has be a digital signal processor for changing the environment conditions by using this we reprogramming easily. This system consists of power converter based on DC to DC full bridge converter and high frequency transformer. This system allows up to 4 KW rating inverters for testing. For designing the P V emulator, Guillermo martin segura used control of IGBT by digital control card to PWM generator which control the output voltage and current of IGBT similar characteristics like real P V module. Guillermo martin explained control strategy and set the load voltage set point by using load current measured and defined V-I curve by using digital signal processor and duty that will control the switching of IGBTs by using two programmed proportional integral controller. Only P I controller is not necessary for converter [1]

Hayrettin CAN simulate and model a photo voltaic panel emulator by using MATLAB Simulink. In Hayrettin CAN project, specification of the system is output voltage rating 18.5V, output current rating 3.5A and power rating 55W. Hayrettin CAN used the same theory for modeling of P V emulator like Gullermo martin segura used system theory. For modeling hayrellin CAN also used DC to DC power converter which is controlled by using field programmable gate array based on pulse width modulation technique. Hayrettin CAN used DC to DC power converter for also different environment condition like partial shadow condition and also different irradiation and temperature. Hayrettin CAN describes the control scheme of P V panel model, first detection circuit samples load voltage and load current with a specified sampling period, next corresponding to the sampled value of current, corresponding output reference voltage will be calculated using P V panel model block. P V panel model block includes the function of irradiation, temperature and load current which produces output reference voltage. Difference between P V panel model block output reference voltage and measured value of load voltage is applied to

proportional controller integral to obtain duty cycle. This duty cycle generate PWM which trigger DC to DC buck converter.[2]

$$V_o = DV_{DC}$$

Tianxiang jiang, Ghanim putrus develop photo voltaic emulator using Lambert function. Specification of this system is output voltage rating is 17.1V, output current rating 3.5A and output power rating is 60 W. Tianxiang jiang describes the MPPT control by using Lambert function. Most widely used method is perturbation and observation method also called hill climbing method. In this method, we search the maximum power point by checking differential coefficient of power with respect to voltage or current but main draw backs of this method is around the optimum voltage point oscillation generates. Second MPPT control method is incremental conductance method, in this method we search maximum power point by using comparison of value of increment conductance (dI/dV) with the conductance (I/V). This method eliminates the oscillation at optimum voltage point but its performance is not good for lower irradiation region but Tianxiang jiang used different of this three MPPT techniques which is called Lambert MPPT control technique. In lambert MPPT control technique, first we implemented controller MATLAB Simulink model. This model determines the optimal voltage at maximum power point based on user's irradiation and temperature data. This optimal voltage is used for reference voltage for calculating maximum power. In this method there is no oscillation at optimal voltage because this controller determines optimal voltage directly without increase or decrease step. Equation used for calculating MPPT for lambert method is [3]

$$V_{Mpp} = \frac{w(e \left(1 + \frac{C_1 \lambda}{C_3}\right) - 1)}{C_4}$$

$$V_{Mpp} = \frac{w(e \left(1 + \frac{(I_{sc} + k(T_c - T_{ref}))\lambda}{\frac{I_{sc}}{e^{\frac{qV_{oc}}{(N_s K A T_c - 1)}}} X \left(\frac{T_c}{T_{ref}}\right)^{3/A} X \left(\frac{qE_G}{KA} \left(\frac{1}{T_{ref}} - \frac{1}{T_c}\right)\right)}\right) - 1)}{\frac{q}{N_s K A T_c}}$$

Dale S. L. Dolan develop photo voltaic panel using Lab view. Dale S. L. Dolan used Solarex MSX-60 specification for developing the emulator. By using the existing model in MATLAB, we obtained the basic algorithm to develop P V Emulator. By using basic algorithm and Sandia data base we modified to be develop different types of P V solar panel. Dale S.L. Dolan used for specified data like panel material used, open circuit voltage (V_{oc}), short circuit current (I_{sc}) and also used Sandia P V data base in Lab view for different irradiance and temperature. By using lab view we change the V-I characteristics based on specified irradiation and temperature. Dale S. L. Dolan write the one diode equation also solve it to calculate output current using newton's methods for fast convergence. This system reflect like real P V panel because user increase or decrease the slider of temperature and irradiation then V I characteristics of panel changes accurately and quickly. Dale S. L. Dolan had developed PV emulator which working at varying of irradiation and temperature condition to use repeatable testing condition. Dale S. L. Dolan developed this type of system for demonstration purpose which is known as SUN POWER 205-BLK. [4]

Ankur V. Rana and Hiren H. Patel develop photo voltaic emulator based on current controlled buck converter. This system rating is open circuit voltage 21V, short circuit current 3.74A, voltage at maximum power point 17.1V, current at maximum power point 3.5A and maximum power is 59.9W. For control circuit of P V Emulator, Ankur V. Rana used buck converter. First Ankur V. Rana develop buck circuit using 100 V input voltage, 25mH rating of inductor and 2000 μ F rating of filter capacitor. The output voltage and current of buck converter are sensed and fed to the controller which output voltage and current controls the converter to behave like photo voltaic emulator. P V module depends on different value of output voltage and current of buck converter but it also depends on irradiation, temperature and load connected across it. To operate P V Module with a specified voltage and current then we control Buck converter with specified vale of irradiation, Temperature, Buck converter output voltage and current.[5]

Yousry Atia, Mohamed Zahran and Abdullah Al-Hossain described data acquisition system for measuring and monitoring the characteristics of photo voltaic solar cell. Yousry used Lab view software and microcontroller with single interface to develop the photo voltaic emulator so whole equipment can be made at low cost and also dark environment characteristics test facility available. Yousry used supervisory monitor personal computer by serial interfacing RS 232 with microcontroller which used the graphical user interface program based on Lab view software. By

using microcontroller and this program it test the solar cell and collect the result and save at monitoring PC and plot result graph. [6]

M.C. Di Piazza, M. Pucci and A. Ragusa design and implemented experimental set up of a grid connected system using Real time photo voltaic emulator. M.C. Di Piazza also develop photo voltaic emulator based on DC to DC converter which is controlled by pole placement technique using photo voltaic V-I characteristics. He used Boost converter as power supply and boost converter is controlled by fuzzy P I regulator. Photo voltaic emulator is used to investigate the whole P V system without using the P V solar panel so it reduced the time and cost for testing the system. To control the inverter of P V system, M.C. Di Piazza used voltage oriented control. [7]

Javier Chavarria, Domingo Biel, Francese Guinjoan, Alberto Poveda, Francese Masana, Eduard Alarcon made low cost photo voltaic emulator for testing grid connected photo voltaic inverters.

This emulator is designed based on DC to DC boost converter. He had discussed in paper that Requirement of emulator arises for testing purposes of new inverters based on SIC devices. javier chavarria also used emulator control using photo voltaic array look up table. Javier chavarria had also used DC to DC Boost converter as power supply. [8]

Antony Xenophontos, Jonathen Rarey, Anthony Trombetta, and Ali M. Bazzi had implement photo voltaic solar power emulator to a flexible low cost. Antony Xenophontos also used the lab view software for modeling purpose. In this paper emulator is developed by off the shell programmable power supply and lab view software without using any peripheral hardware. For this system equivalent resistance and output solar panel is calculated using resistance tracking technique. In this paper he also used current source topology in place of power supply. He had used coding and communication algorithm to improve the result during panel shading model and analytical model. [9]

Thomas Geury, Johan Gyselinck developed photo voltaic emulator with shading effects for testing the grid connected system. For Thomas Geury used single exponential model of solar cell

with approximation. For measurement of reference output voltage and output current of emulator we used retroactive loop for P V modeling. This system consists of power converter based on DC to DC full bridge converter and high frequency transformer and also used pulse width modulation signal to DC to DC converter. For simulation purposes Thomas Geury used graphical user interface to modify test parameters and compare the results online so we properly observe maximum power point and connection of inverter is easy at grid connected system. [10]

Jaya Agrawal, Mohan Aware describes photo voltaic emulator in his paper. Jaya agarwal also used lab view software and real data acquisition system to simulate photo voltaic system. Jaya Agarwal explains development of P V emulator by using real time algorithm of solar cell module and calculate scaled output power by input AC- DC power. By using graphical user interface, photo voltaic solar array parameter details to be configured to emulate PV emulator and also using sensor equivalent output voltages, we emulate the P V panel with varying temperature and irradiation condition. This laboratory develop system will be tested at real time P V model for static and dynamic condition and also calculate the maximum power point of this system using Golden search algorithm.[11]

Rupesh G. Wandhare and Vivek Agarwa had described to emulator of low cost. High accuracy, compact photo voltaic emulator in his paper. This emulator gives specified V I characteristics with varying temperature and irradiation and also its ability to reconfigured for series and shunt connection of P V panel. Rupesh G. Wandhare used some specified data like open circuit voltage 21V, short circuit current 2A and value of irradiation $1000 \frac{W}{m^2}$ and output power is about 150W using combination of series and shunt connection. Fly back converter is used for DC input power which is the heart of Photo voltaic emulator. He used PIC microcontroller for control and monitoring purposes and also 3 type compensator controls the output voltage and current of P V emulator. 3 type compensator designed by using K factor for good dynamic response. He developed hardware with light weight about 1 Kg. [12]

Woojoo Lee, Younghyun Kim, Yanzhi Wang, Naehyuck Chang, Massoud Pedram, and Soohee Han developed high fidelity versatile photo voltaic emulator. He used controller power supply by using bi directional converter, DC to DC buck converter, full bridge converters and high

frequency transformers. This system describes architecture P V emulator system with sensor board and emulator board. We calculate the angle and direction of incident sun light irradiation by using magnetic sensor and accelerometer which is Honeywell HMC6042 and Freescale MMA7260Q. [13]

N. Pandiarajan and Ranganath Muthu explains photovoltaic modeling in Simulink he does not implement hardware of photo voltaic module. In this paper N. pandirajan describes the step by step procedure to simulate photo voltaic module and describes one diode equivalent circuit model and plot V I and P V characteristics with 36W solar photo voltaic module. He used some specification rating like open circuit voltage 21.24V, short circuit current 2.55A, voltage at maximum power point 16.56V, current at maximum power point 2.25A, total number of series cell 36, total number of shunt connected cell 1 and output power rating 37.08W.[14]

C.H. Balakishan, N. Sandeep developed microcontroller based photo voltaic emulator using current controlled DC to DC buck converter. This paper explains the new algorithm to implement P V emulator by using DC to DC buck converter and microcontroller. Used algorithm tracks the V I characteristics of P V module with varying loads and the output reference current. This reference output current is used to produce the PWM pulses to trigger gate terminal of DC to DC converter. By using the time varying input we implement varying condition of temperature and irradiation. C H balakishan used ATmega328 microcontroller and 50W rating of DC to DC buck converter. [15]

CHAPTER 3

MODELING OF P V SOLAR PANEL

3.1 Basic one Diode Model

The main theme of photo voltaic emulator is to its output current follows the characteristics of diode equivalent model as closely as possible. We used the simplified model of P V emulator to simulate a solar panel also different models can be made with difficulties to model a P V module. In practical model, shunt resistance value is very less in modules and calculation for output and voltage will be more complex. For ideal model, value of $R_s=0$ so there will be no voltage drop before load and also value of $R_{sh}=\infty$ (actual value of R_{sh} is greater than 200Ω).

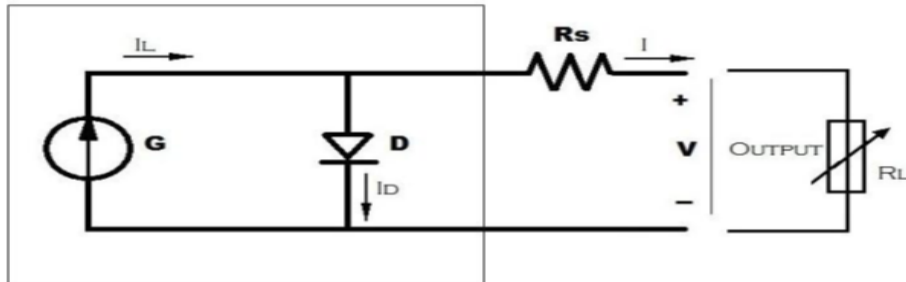


Fig3.1:- equivalent circuit of one diode ideal model

$$\text{LOAD CURRENT (I)} = I_L - I_D \quad (1)$$

$$\text{LOAD CURRENT (I)} = I_L - I_0 \left(e^{\left(\frac{q(v + R_s I)}{nKT} \right) - 1} \right) \quad (2)$$

Output solar cell saturation current and photo electric current depends on the temperature. This equation describes depending parameter of irradiation and temperature that affects the behavior of solar panel.

$$I_L = I_L(T_1) + K_0(T - T_1) \quad (3)$$

$$I_L(T_1) = I_{SC}(T_{1nom}) \frac{G}{G_{nom}} \quad (4)$$

$$K_0 = \frac{I_{sc}(T_2) - I_{sc}(T_1)}{(T_2 - T_1)} \quad (5)$$

$$I_0 = I_0(T_1) \left(\frac{T}{T_1}\right)^{3/n} * e^{\frac{-qV_g(T_1)(\frac{1}{T} - \frac{1}{T_1})}{nk}} \quad (6)$$

$$I_0(T_1) = \frac{I_{sc}(T_1)}{\left(\frac{qV_{oc}(T_1)}{nkT_1} - 1\right)} \quad (7)$$

Series resistance depends on temperature, equation 8 shows that how series resistance depends on temperature and equation 9 shows series reactance depends on saturation current.

$$R_s = \frac{dV}{dI_{voc}} - \frac{1}{X_v} \quad (8)$$

$$X_v = I_0(T_1) \frac{q}{nkT_1} e^{\frac{qV_{oc}(T_1)}{nkT_1}} \quad (9)$$

This solar cell model takes two fixed temperature for calculating the output voltage of solar cell at 0 kelvin temperature.

3.2 Solar module performance parameter

Solar module performance depends on following parameter discuss below

- Short circuit current
- Open circuit voltage
- Maximum power
- Current at maximum power
- Voltage at maximum power
- Fill factor
- Efficiency

3.2.1 Short circuit current

Short circuit current produced by collection and generation light generated carriers. Light generated current and photo electric short circuit currents are equal for ideal solar cell.

Short circuit current depends on different parameters which is explained below

- Area of solar cell: - if we want to remove dependence of area of solar cell then we list short circuit current density without knowing short circuit current.
- Number of photons: - it means incident light power. Short circuit current directly depends on incident light intensity i.e. energy of photon.
- Spectrum of incident light: - in previous pages I discuss about irradiation spectrum in which visible light spectrum is mostly absorbed by solar cell or solar panel.
- Optical properties:-It describes the reflection and absorption of solar cell.

When solar cell is manufactured with same material which is mostly depends on two parameters like surface coating and diffusion length. For perfectly coating surface and uniform generation in cell, short circuit current equation can be explained as:

$$J_{sc} = qG(L_n + L_p) \quad (10)$$

Where G is the irradiation rate, and L_p and L_n are the hole and electron diffusion lengths. This equation also makes some assumptions but this is not applicable in most of solar cells. This equation shows that short circuit current is directly proportional to irradiation rate and hole, electron diffusion length.

Solar cells under solar spectrum irradiation of AirMass1.5 reference have a maximum current about 46 mA/cm². Short circuit current is measured about 42 mA/cm² when solar cell is used in laboratory and short circuit currents is measured between about 28 mA/cm² to 35 mA/cm² when solar cell used for commercial purposes.

3.2.2 Open Circuit Voltage (VOC):-

At zero load current, the maximum voltage present at solar cell is called open circuit voltage. The open circuit voltage defined by the amount of forward bias on the photo cell due to the bias of the photo cell junction with light generated current.

Open circuit voltage is calculated by setting the load current equal to zero that equation is

$$V_{oc} = \frac{nkT}{q} \ln \left[\frac{I_L}{I_o} + 1 \right] \quad (11)$$

In this equation, we explain the open circuit voltage. Open circuit voltage depends on saturation current and light generated current of solar cell. In comparison of open circuit voltage, short circuit current has small variation due to saturation current and saturation current depends on recombination of solar cell. Open circuit voltage has determined by amount of solar cell recombination and it depends on which type of material used. Open circuit voltage is about 730mV under one cell when single crystalline material used in solar cell but if we used multi crystalline material for solar cell material then open circuit voltage is about 600mV.

Open circuit voltage is determined by another method using carrier concentration which is explained below.

$$V_{oc} = \frac{kT}{q} \ln \left[\frac{(N_A + \Delta n)\Delta n}{n_i^2} \right] \quad (12)$$

Where

kT/q = thermal voltage

N_A = the doping concentration,

Δn = excess carrier concentration

n_i = intrinsic carrier concentration.

3.2.3 Maximum power, voltage at maximum power, current at maximum power

Solar cell output power can be calculated by V I characteristics of photo voltaic by using equation $p=V *I$. maximum output power occurs between open circuit voltage and short circuit current. When maximum power occurs at that time voltage is represent maximum voltage and current represent maximum current.

3.2.4 Fill factor

The Fill Factor explains the quality of the photo voltaic solar cell. Fill factor is the ratio between maximum powers to the theoretical power it is calculated by comparing the maximum output power to the theoretical. Fill factor is key parameter which show the performance of solar cell. Fill factor is defined in graphically then it is ratio of rectangular areas. Below equation explain the fill factor

$$FF = \frac{P_{\max}}{P_T} = \frac{I_{MP}V_{MP}}{I_{sc}V_{oc}} \quad (13)$$

Fill factor depends on grade of solar cell if we use high grade of solar cell in commercial use then its fill factor is about greater than 0.7 and if we use low grade of solar cell then fill factor is between 0.4 to 0.7.

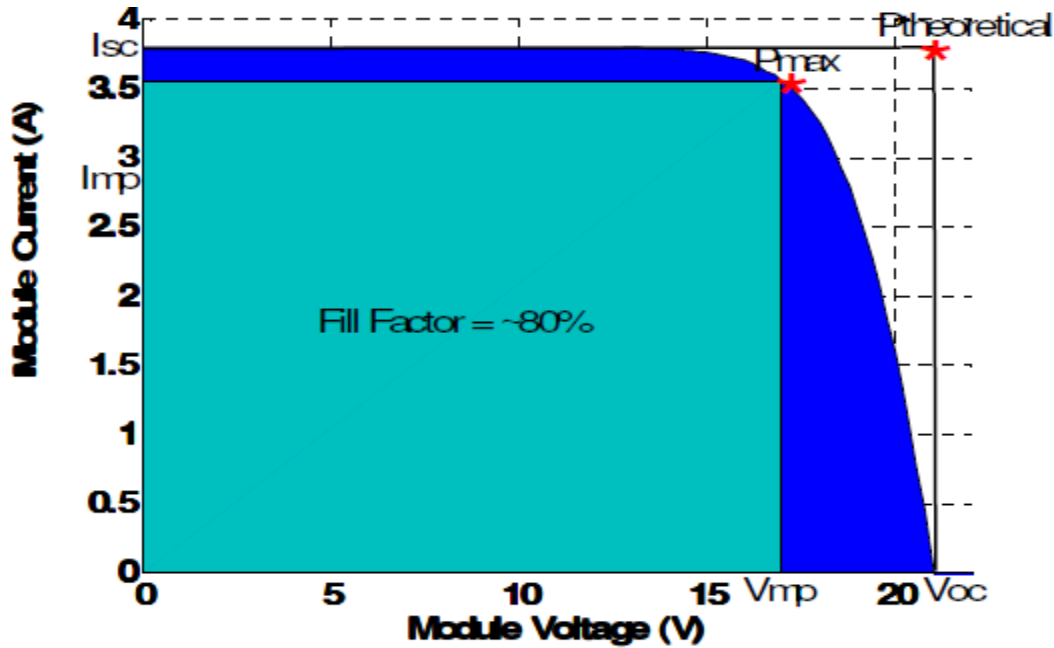


Fig3.2:- fill factor of solar cell

Fill factor affect due to series and shunt resistance losses. If any system fill factor is 100% then series and shunt resistance losses are zero.

3.2.5 Efficiency

Efficiency of solar cell is the ratio of output power generated to the input power. In place of output power if we take maximum output power then maximum efficiency of solar cell has been calculated.

$$\eta_{max} = \frac{P_{out}}{P_{in}} \quad (14)$$

In previous pages I discussed only one diode model or single photo voltaic cell. Below figure shows complete diode equivalent model of photo voltaic module which is composition of series parallel combination of single photo voltaic cells. Practical solar panel diode model includes series and shunt resistances losses but simplified solar panel diode model does not include shunt resistances but include series resistance and for ideal solar panel diode model does not include any of series and shunt resistance. The model that has been discussed is for a single photovoltaic cell. If we want to increase the amount of output voltage of solar panel module then we add the individual solar cells in series and if we want to increase the amount of output current of solar panel module then we add solar cells in parallel. Adding solar cell in series is related like we add some batteries in series and add up total voltage level similarly adding solar cell in parallel is equal to some batteries add in parallel and individual battery output current add up together.

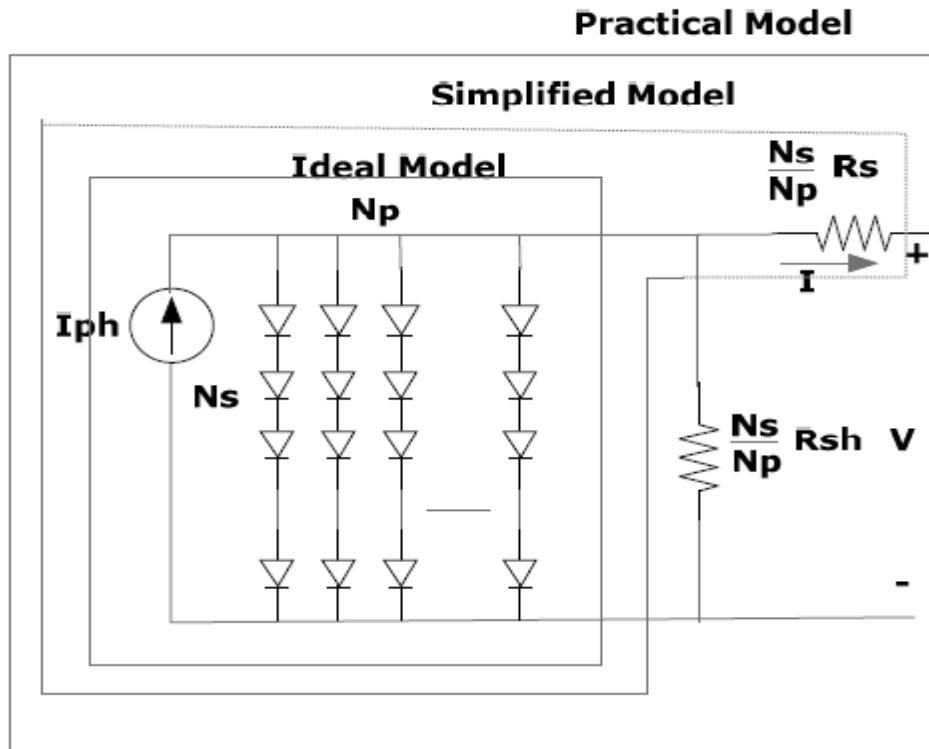


Fig3.3:-different types of solar panel model

3.3 Curve analysis

V I and P V curve represented the electrical characteristics of solar cell. First I explains the V I curve and P v curve then I explain how V I and P V curve changes when varying the value of irradiation, temperature, connection of more cells in series or in parallel and diode quality factor. When we connect photo voltaic simulator to resistive load then it meet ohm's law by this theory it is clear that output of solar panel power depends on value of load resistance.

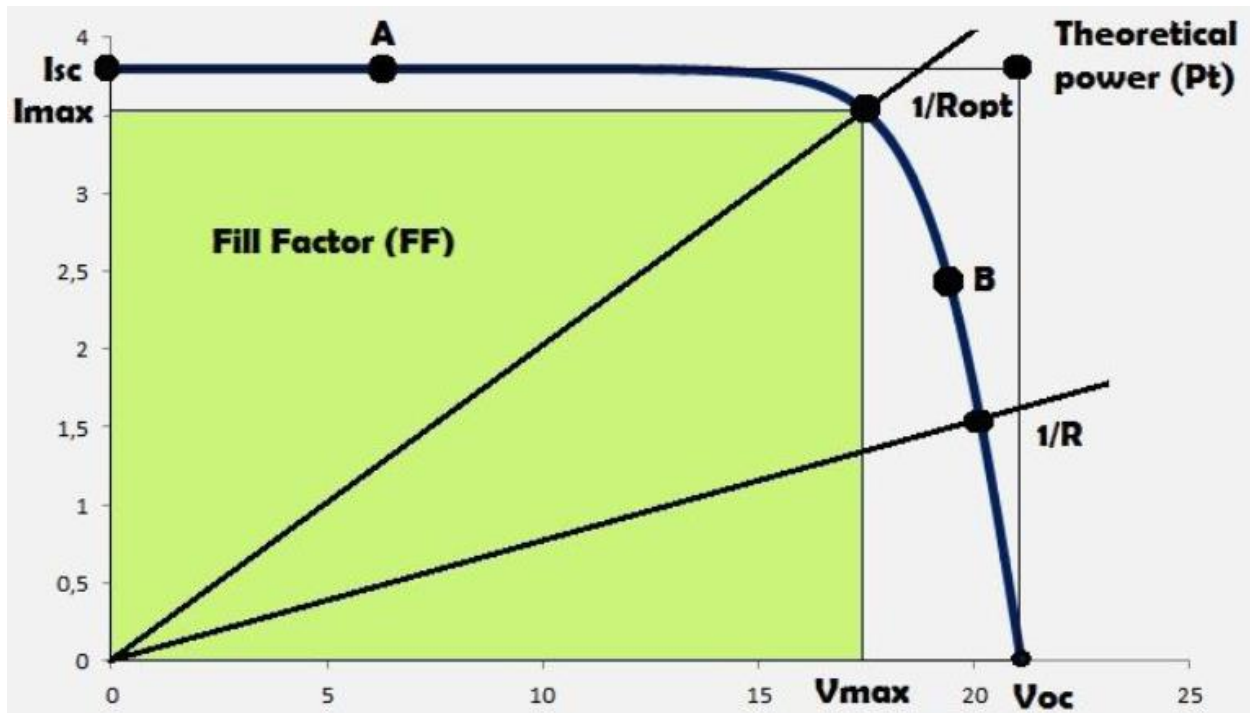


Fig3.4:- V I curve for photo voltaic solar cell

When R is small value then output of solar panel lies at left of maximum power which is point A, where behavior of solar panel is like current source and if value of R is equal to zero then output of solar panel lies at short circuit point and output power of solar panel is zero. Similarly if value of R is large then output of solar panel lies at right of maximum power which is point B, where behavior of solar panel is like voltage source and if value of R is equal to infinite then output of solar panel lies at open circuit voltage point at this point output power is zero. We calculate specific value of resistance to calculate maximum output power using fill factor. In this diagram we calculate value of resistance by the ratio of green portion of the diagram to the white portion of the diagram to produce maximum solar panel power.

$$\text{value of resistance} = \frac{\text{green portion}}{\text{white portion}} = \frac{P_{\max}}{P_T} = \frac{I_{MP}V_{MP}}{I_{SC}V_{OC}}$$

Power curve is the product of output voltage and output current. Photo voltaic solar systems are designed like it works at its maximum power point region and also inverters used in solar system are designed to work a range of maximum voltage to minimum voltage across the maximum power point range so inverters work properly and also find solar plant is working at which maximum power point. It is very important that output voltage of solar panel is not exceeded the limit of

inverter voltage range in any case when p v module works at open circuit and minimum irradiation or temperature or both.

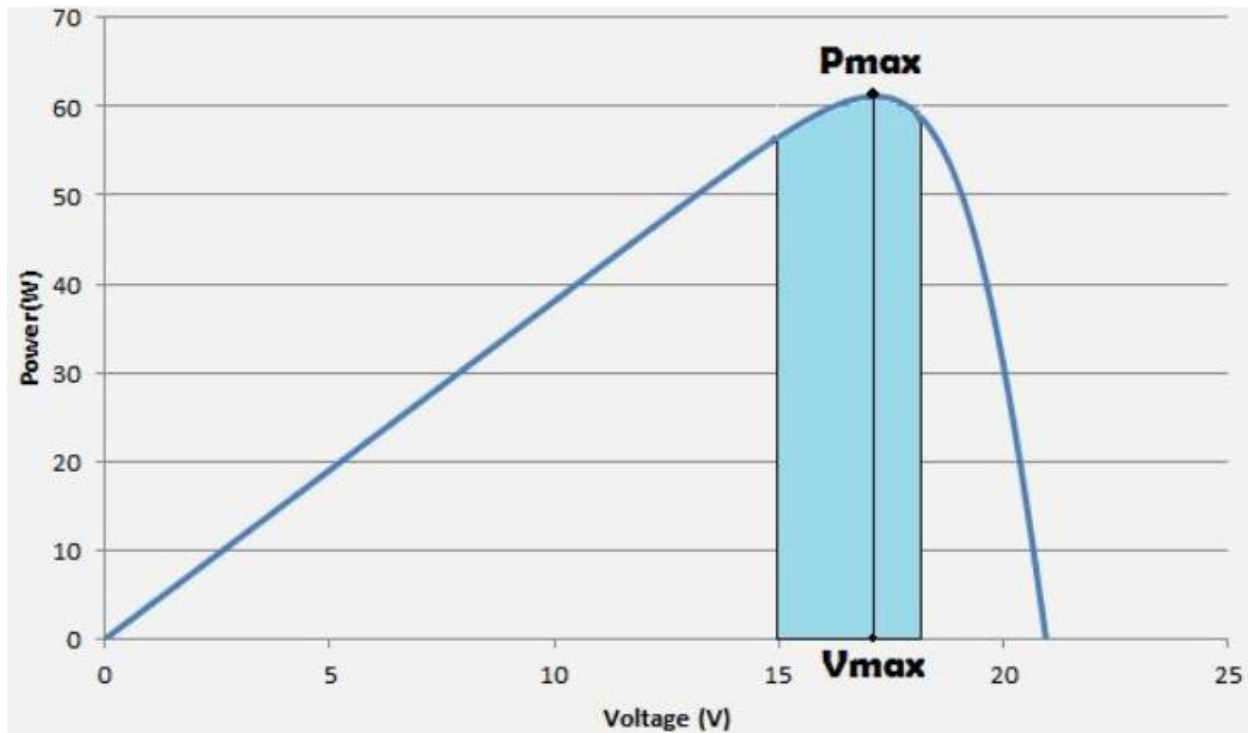


Fig3.5:- standard P V curve for solar module

When solar module is used for commercial or practical purposes then difficulty occurs to connect solar panel with inverter. Main cause is that we don't know solar panel voltage and inverter voltage at that instant of time because changing of irradiation and temperature. so by using the photo voltaic simulator we find voltage at maximum power point then by using photo voltaic emulator we programmed to fix that voltage and connect to inverter for testing purposes and also the behavior of system.

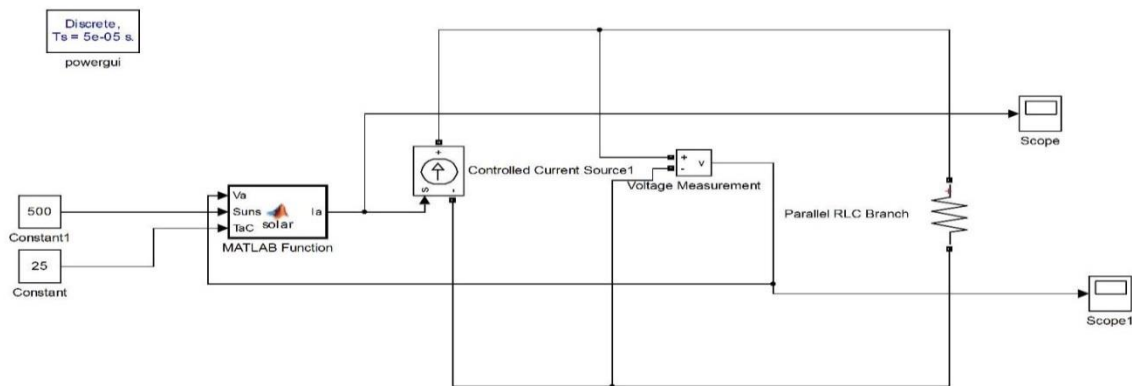
CHAPTER 4

SIMULATION AND ITS RESULT

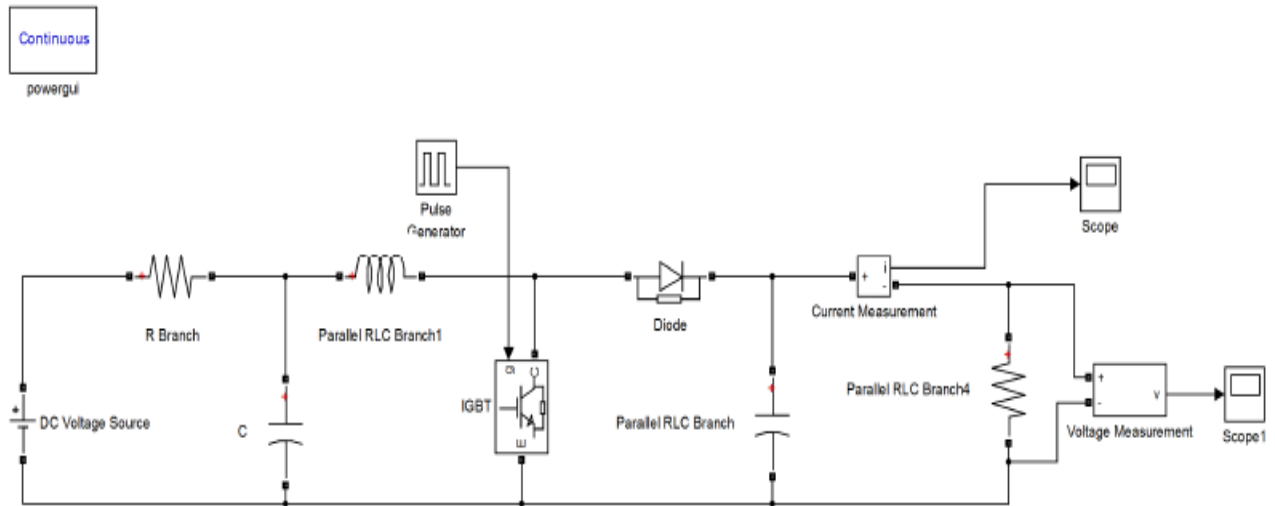
4.1 SIMULATION

Figures 4.1.1 and 4.1.2 shows MATLAB simulation model diagram of a boost converter by using MATLAB 2013a software. While Figures 4.1.3 show a MATLAB simulation model of complete diagram of boost converters with P&O MPPT and PV module using MATLAB 2013a software. The (Fig.4.1) and (Fig.4.3) explains the dependence of the photo voltaic solar cells as a function of incident solar irradiance. The curves correspond to different irradiancies 1000 W/m², 750 W/m², 500 W/m², 250 W/m² at constant temperature 25°C. This curve shows that if incident solar irradiation is increasing at constant temperature then output power also increase. The Figure 4.2 and Figure 4.4 explains the behavior of the photo voltaic cells when we increase or decrease temperature. The curves shows photo voltaic solar cell behavior at different temperature like 0°C, 25°C, 50°C, 75°C. This graph shows that if value of temperature increased then power of solar cell decrease.

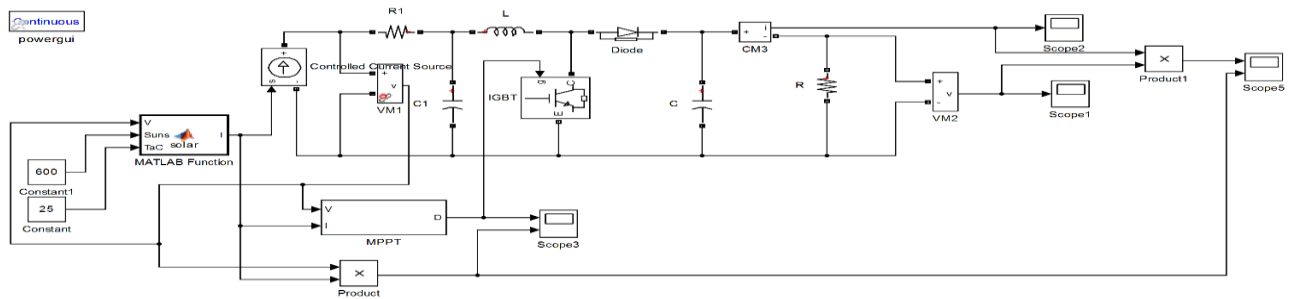
4.1.1 SIMULATION CIRCUIT OF BASIC PV PANEL



4.1.2 SIMULATION CKT OF BOOST CONVERTER



4.1.3 SIMULATION CKT OF PV PANEL WITH MPPT AND BOOST CONVERTER



4.2 OUTPUT MATLAB WAVEFORMS

CASE-1 VI CURVE FOR DIFFERENT IRRADIATION

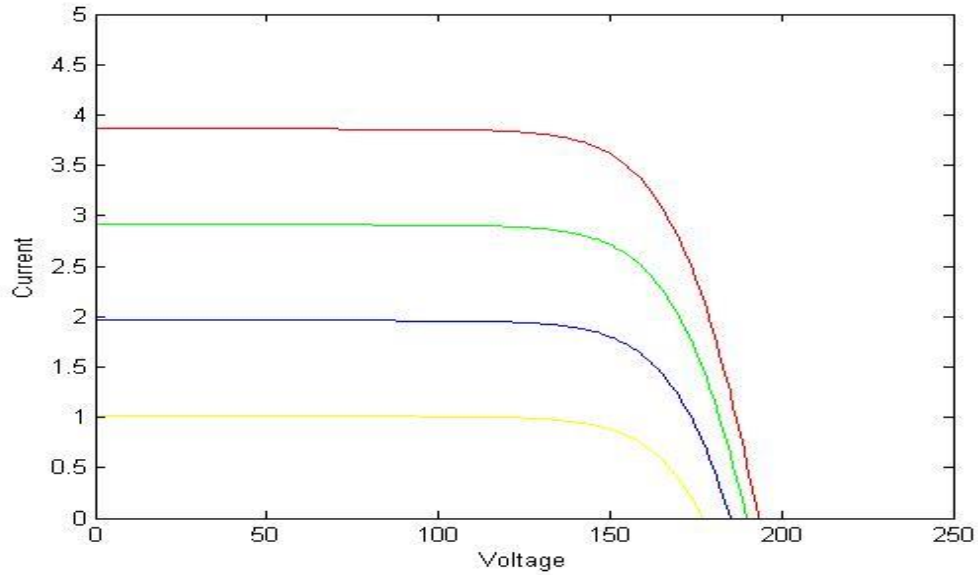


Fig 4.1:- VI curve For $1 \frac{kw}{m^2}$, $0.75 \frac{kw}{m^2}$, $0.5 \frac{kw}{m^2}$, $0.25 \frac{kw}{m^2}$ Irradiation

CASE-2 VI CURVE FOR DIFFERENT TEMPERATURE

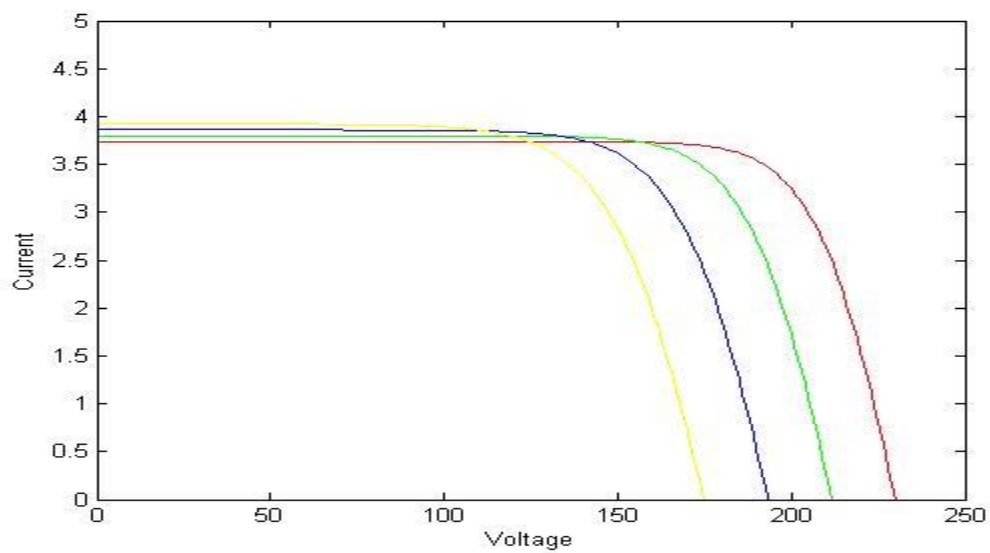


Fig4.2:- VI curve for $0^{\circ}C$, $25^{\circ}C$, $50^{\circ}C$, $75^{\circ}C$ Tem

CASE-3 PV CURVE FOR DIFFERENT IRRADIATION

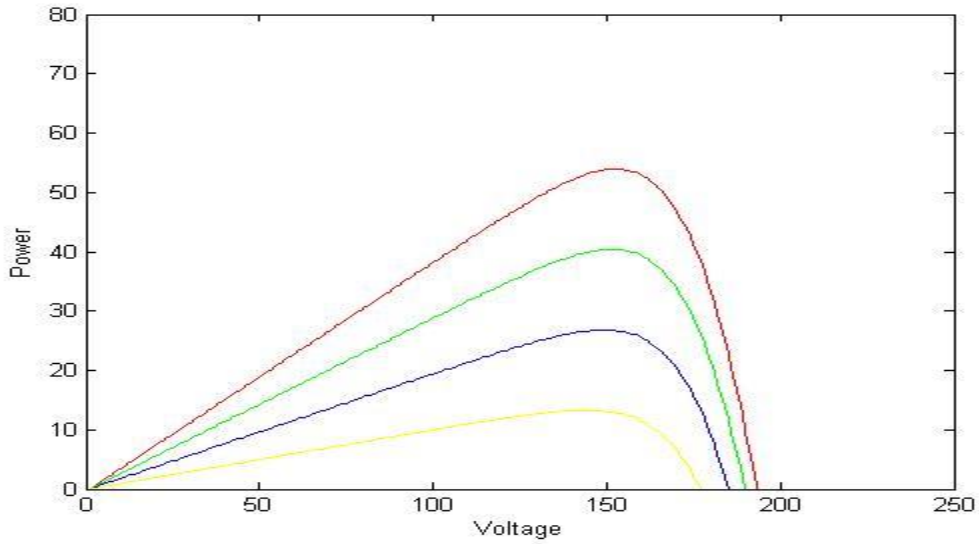


Fig 4.3:- PV curve For 1 $\frac{kw}{m^2}$, 0.75 $\frac{kw}{m^2}$, 0.5 $\frac{kw}{m^2}$, 0.25 $\frac{kw}{m^2}$ Irradiation

CASE-4 PV CURVE FOR DIFFERENT TEMPERATURE

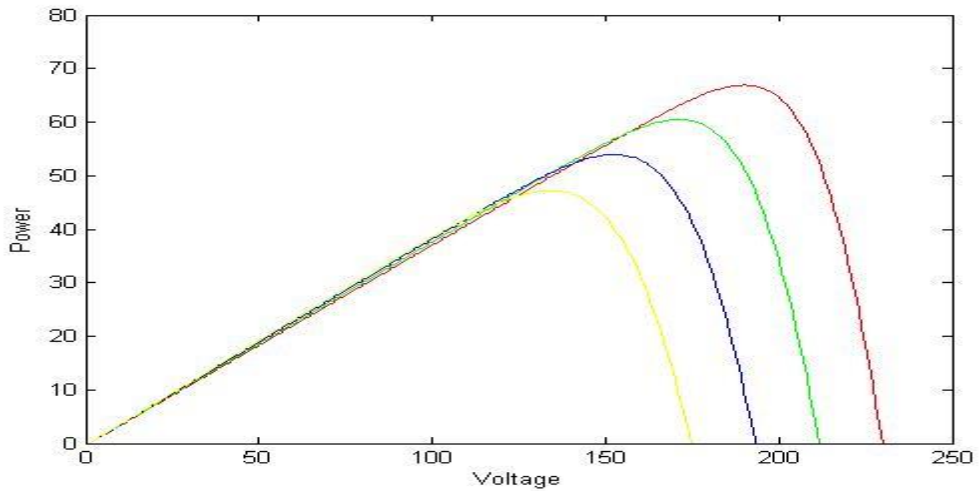
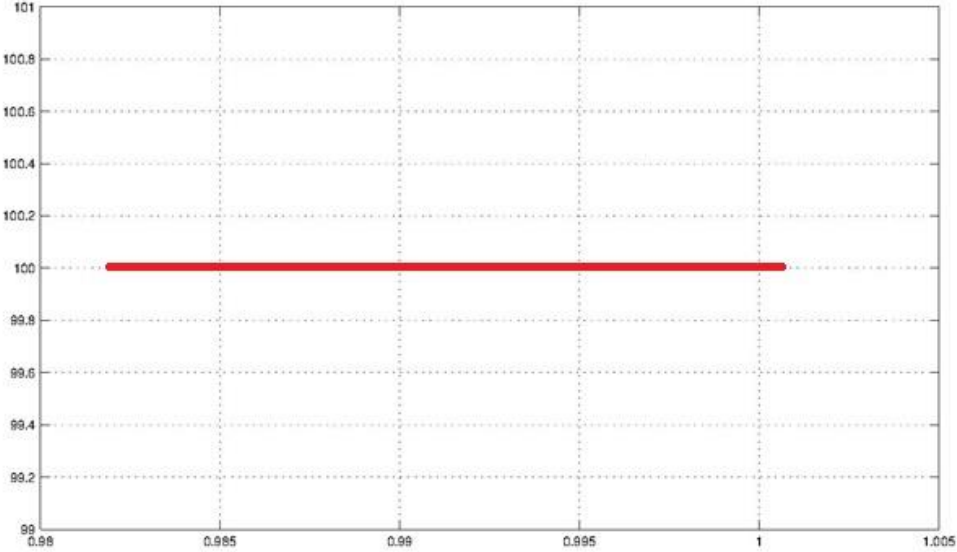
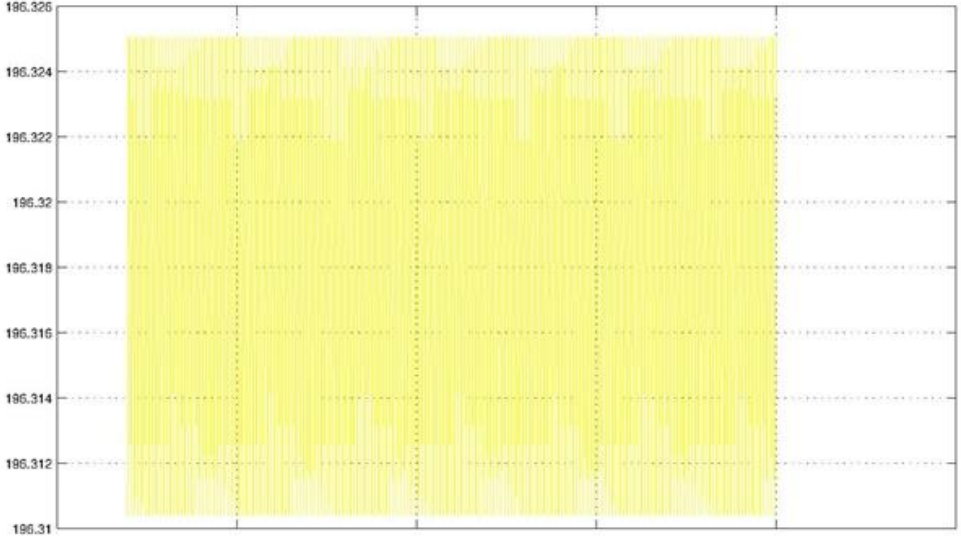


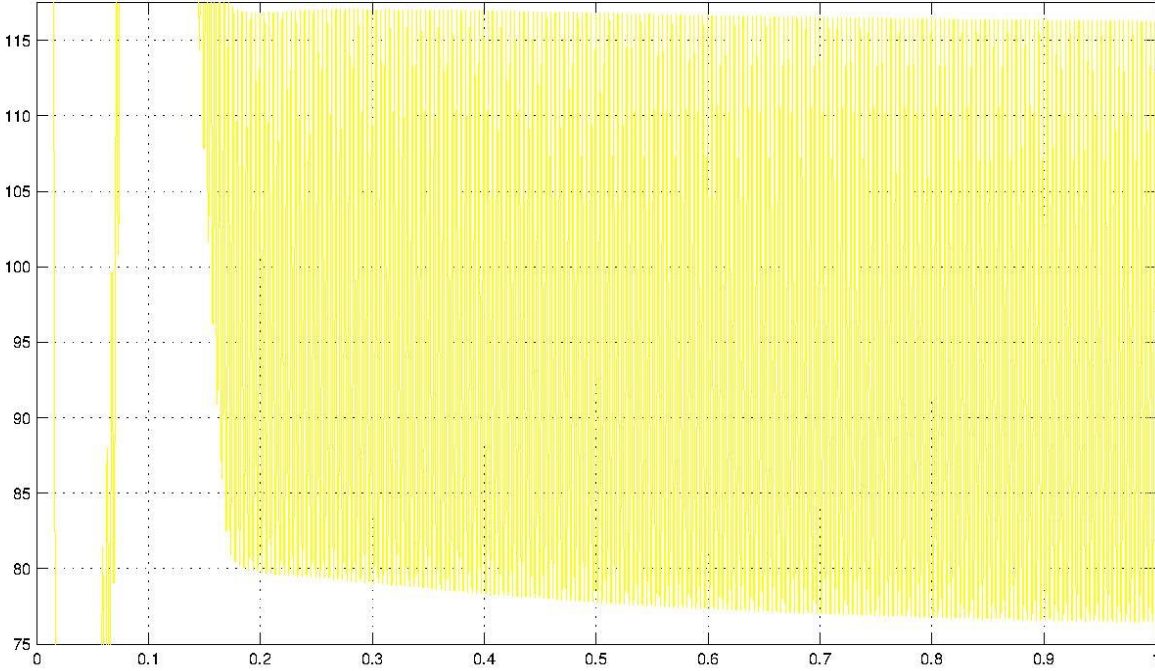
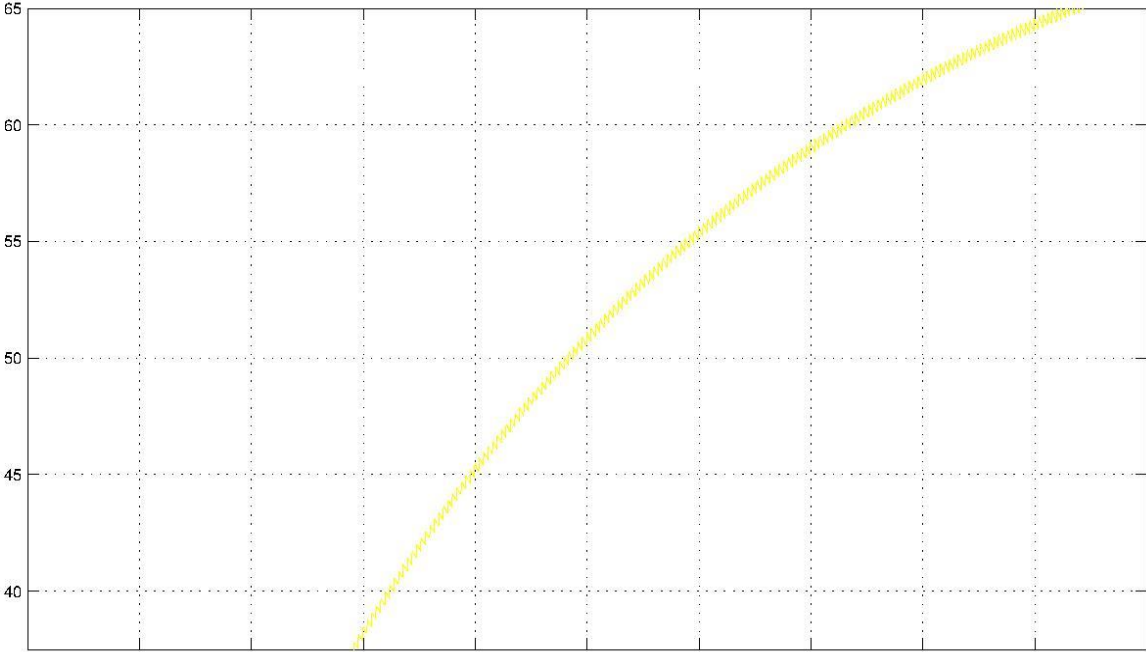
Fig4.4:- PV curve for 0°C, 25°C, 50°C, 75°C Tem

4.3 SIMULATION RESULT FOR BOOST CONVERTER (Output voltage Curve)



Time offset: 0

4.4 SIMULATION RESULT WITH MPPT POWER AND WITHOUT MPPT POWER

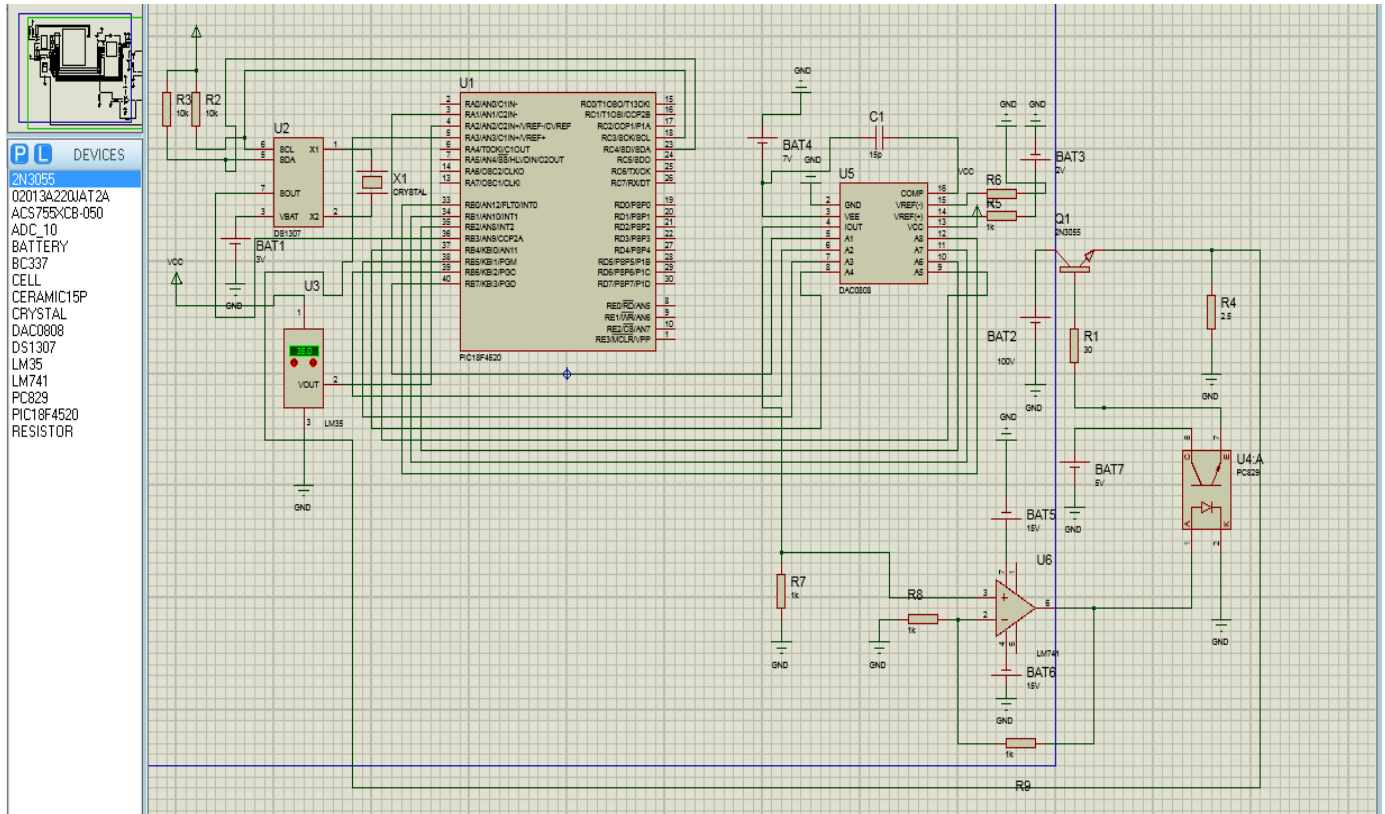


Time offset: 0

CHAPTER 5

HARDWARE IMPLEMENTATION OF PV EMULATOR

5.1 Schematic of hardware module



5.2 Description of individual module

5.2.1 Real time clock DS1307

Real time clock which is available in integrated circuit form uses crystal oscillator with frequency of oscillation is 32.768 KHz. when start condition is implemented and providing device code with register address than subsequent registers can be accessed before stop condition is executed.

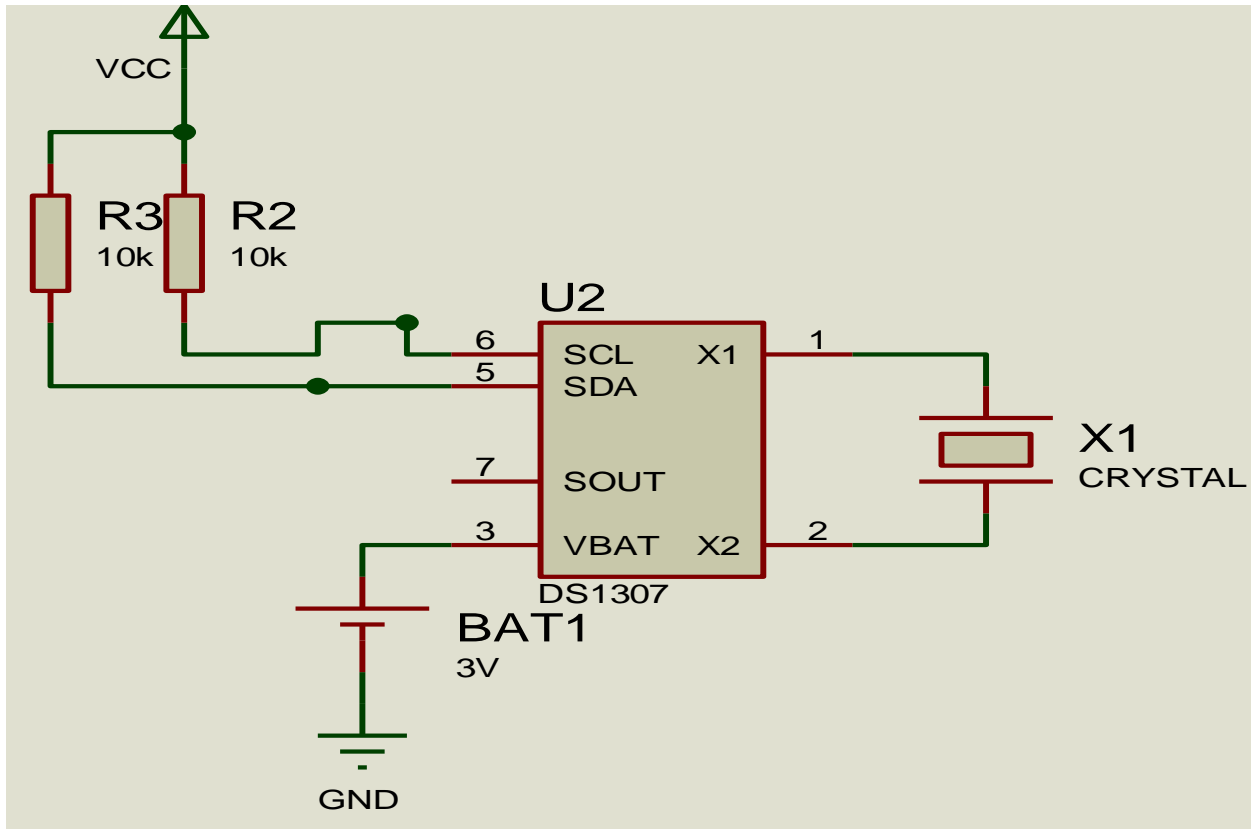


Fig5.1:- connection diagram of real time clock

The control register of RTC can be written manually to operate on required frequency which is 32.768 KHz.

BIT 7	BIT 6	BIT 5	BIT 4	BIT 3	BIT 2	BIT 1	BIT 0
OUT	0	0	SQWE	0	0	RS 1	RS 0

When OUT=1; It levels the output as logic '1' when square wave output is disabled and vice versa.

SQWE=1; It enables the square wave output.

RS=Rate select; It controls the frequency of square wave output by selecting the combination of RS bits as follows

RS 1	RS 0	SQW/OUT frequency
0	0	1Hz
0	1	4.096kHz

1	0	8.192kHz
1	1	32.768 KHZ

Serial clock Input (SCL):-It is used to synchronize data transfer in serial interface. This signal is connected to pin no. 14 of PIC microcontroller to synchronize the clock serially.

Serial Data Input/output (SDA):- It is 2 wire serial interface to input/output pin which is connected to pin no. 15 of PIC microcontroller to synchronize the data serially.

For Vcc we applied 5V DC input so that data can be read & write. If the value of Vcc goes to below $1.25 \times V_{BAT}$ than data are inhibited for read & write. We used $V_{BAT}=2V$.

5.2.2 Temperature sensor LM35

It senses the ambient temperature and converts into voltage signal while operating with input voltage range of 4V-20V. We have used the input voltage=10 V. The output of sensor is fed to the input pin no.04 (AN2) of PIC microcontroller.

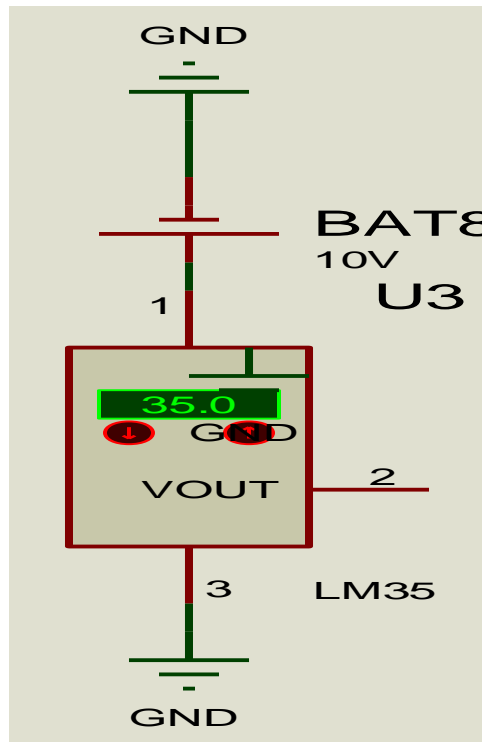


Fig5.2:- connection Diagram of temperature sensor

5.2.3 PIC Microcontroller 18F4520

PIC 18F4520 is a 8 bit microcontroller having 4 port each of 8 bit bidirectional data port and 1 port of 4 bit bidirectional data port, 32KB of flash memory which is eventually used for program memory and data memory, 10-bit analog to digital converter are used which has 13 channel for analog signals, Indexed addressing modes are used in programming of PIC and it has instruction set of 8 bits, USART module which is inbuilt in PIC is used for serial communication to outside chips which uses standard RS-232 for operation and we used I²C mode for serial communication between RTC1307 and PIC 18F4520.

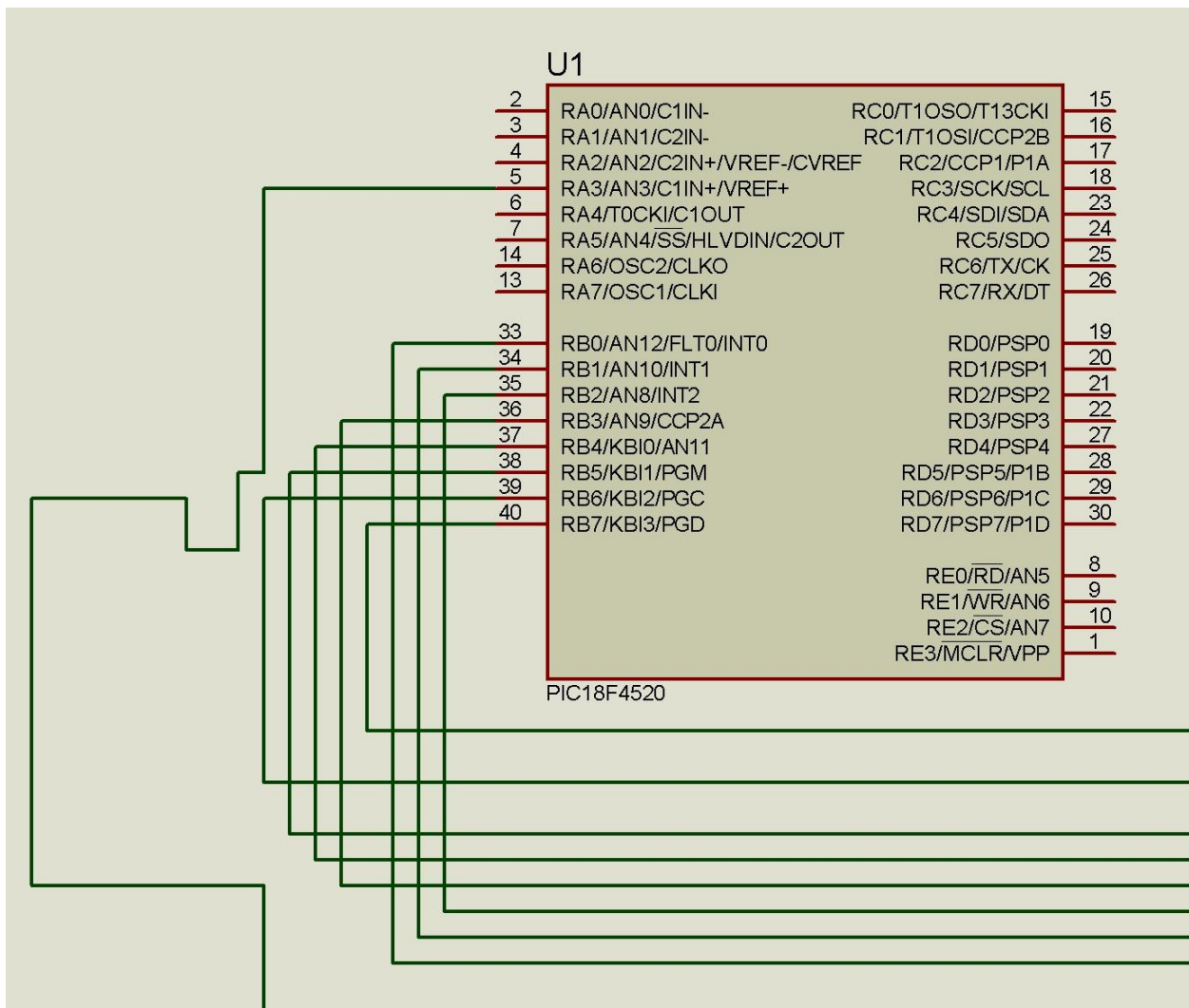


Fig5.3:- connection Diagram of PIC 18F4520 Microcontroller

Different pin of PIC used in implementation

Pin no.33-40 of PIC which is part of PORT B are used in our implementation as output data pin. Output of these pin is fed to the 8 bit DAC 0808 which converts the digital signal into analog signal carrying the information of irradiation of sunlight which is obtained from NREL's spectral solar radiation database and temperature of ambient which is obtained by temperature sensor LM35. The program is written in C language in MikroC where we provided the input parameters as irradiance, temperature and output reference voltage. The current equation is obtained after considering the solar panel as equivalent of one diode model.

Pin no.3-5 of PIC which is part of PORT A are used as input data pin. Pin no. 3 is connected to SQW/OUT of RTC, pin no.4 is connected to output of temperature sensor and pin no.5 is connected to output reference voltage coming from high current BJT power amplifier.

A/D control register

We have used ADCON0 register which controls the operation of A/D module. It is a 8 bit register which is configured as follows

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	—	CHS3	CHS2	CHS1	CHS0	GO/DONE	ADON
bit 7							bit 0

CHS<3:0>: Analog Channel Select bits

0000 = Channel 0 (AN0)
0001 = Channel 1 (AN1)
0010 = Channel 2 (AN2)
0011 = Channel 3 (AN3)
0100 = Channel 4 (AN4)
0101 = Channel 5 (AN5)^(1,2)
0110 = Channel 6 (AN6)^(1,2)
0111 = Channel 7 (AN7)^(1,2)
1000 = Channel 8 (AN8)
1001 = Channel 9 (AN9)
1010 = Channel 10 (AN10)
1011 = Channel 11 (AN11)
1100 = Channel 12 (AN12)
1101 = Unimplemented⁽²⁾
1110 = Unimplemented⁽²⁾
1111 = Unimplemented⁽²⁾

We have used channel from 1-3 for our 3 analog signals namely irradiation, temperature and voltage.

5.2.4 8 bit DAC0808

DAC0808 IS 8 Bit digital to analog converter with a full scale output current setting time of 150nS. Pin no.5-12 of DAC is connected to pin no.33-40 of PIC for the conversion of digital information into analog information .

We used $V_{ref+} = 10\text{ V}$, $V_{ref-} = \text{Gnd}$ and $V_{EE} = -5\text{V}$ for the purpose of conversion of bits into analog signal which is described as

$$I_O = K \left(\frac{A1}{2} + \frac{A2}{4} + \frac{A3}{8} + \frac{A4}{16} + \frac{A5}{32} + \frac{A6}{64} + \frac{A7}{128} + \frac{A8}{256} \right)$$

where $K \cong \frac{V_{REF}}{R14}$

$R14 = 8\text{K}\Omega$

This output is further amplified by the Op-Amp to have sufficient level of voltage for the opto-coupler. Schematic of DAC is shown below.

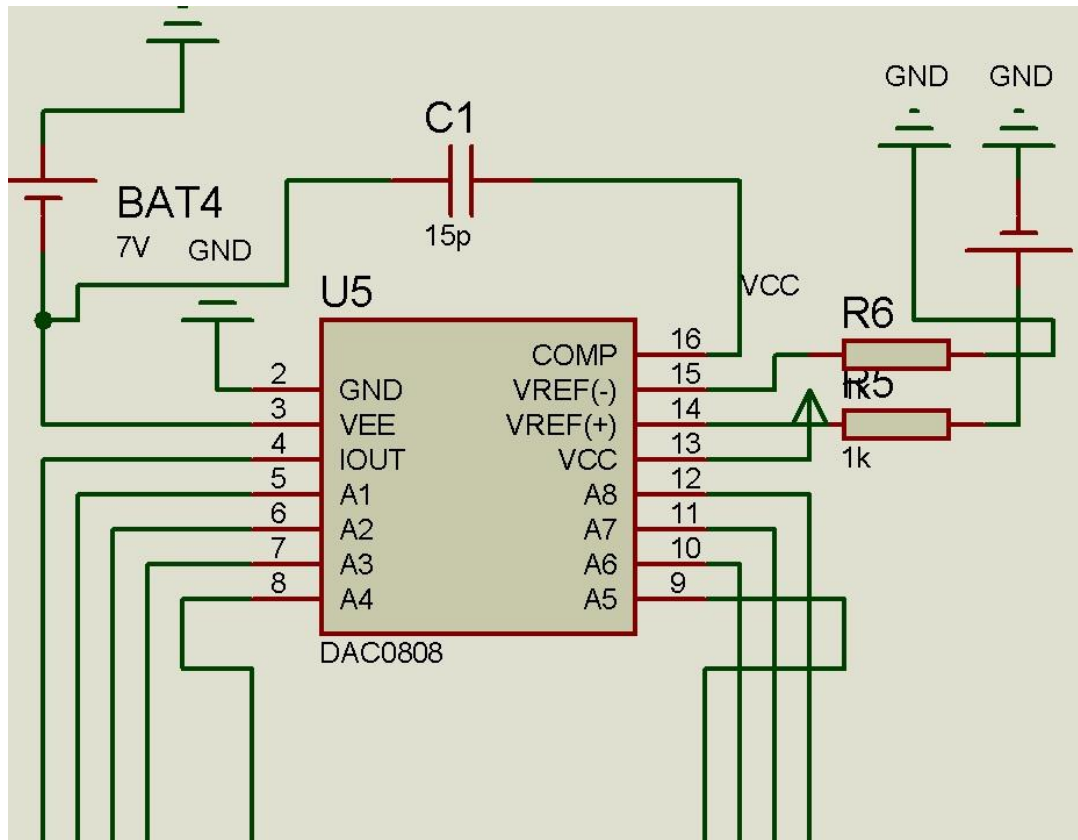


Fig5.4:- Connection Diagram of DAC0808

5.2.5 Op-Amp LM741

It is a general purpose operational amplifier used as voltage amplifier so that opto-coupler which is used in next stage can sense the minimum voltage. We used $V^+ = 15V$, $V^- = 15V$ and non-inverting input terminal for input signal. Value of resistances are set to obtain the gain value of 40.

5.2.6 Opto-coupler ILD74

Dual channel opto coupler is used for electrical isolation which used IR LED at the input side which is optically paired with phototransistor at the output side. This transistor should operate on the linear region so that output information is linearly related with input. Here opto-coupler worked as switch

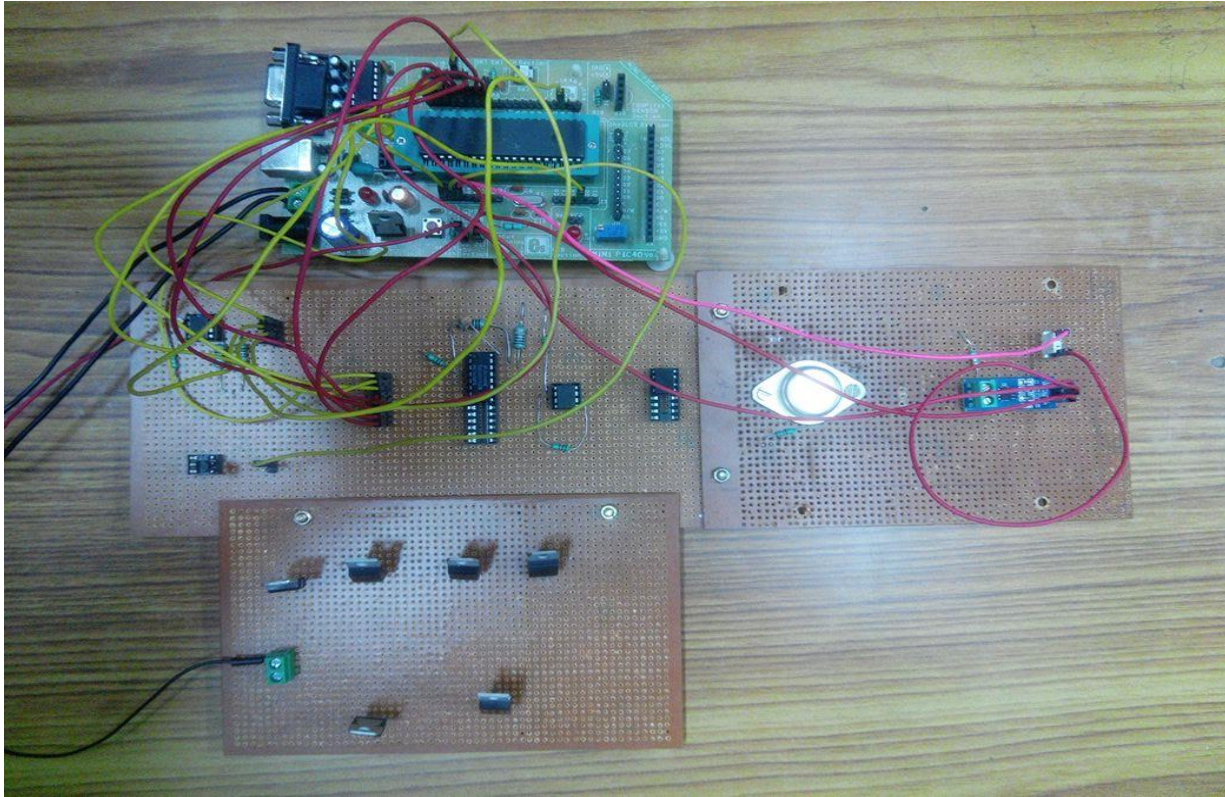
5.2.7 High power BJT 2N3055A

High power BJT is used to obtain the current value of 1A. We designed the circuit as base voltage $V_{BB} = 5V$, $R_B = 50\Omega$, $V_{CC} = 10V$, $R_E = 2.5\ \Omega$ with $\beta = 90$.

5.2.8 Current sensor ACS712

It converts the current into voltage by the principle of Hall Effect. This voltage is given as feedback to PIC microcontroller.

5.3 Proposed Hardware model



5.4 Result Obtained from Hardware Model



The expected output voltage is constant which are shown in the figure above.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

Recently there is renewed interest in generation of electricity from PV based renewable system. However for the testing and development of power system we need to implement photo voltaic Emulator. The photo voltaic Emulator is able to test the grid connected Inverters and MPPT algorithm like in the real environment. Photo Voltaic emulator has ability to implement greater than 100 Solar Panel with different environment condition. We have implemented single panel of PV module with different irradiation and temperature. This P V Emulator should test Kilo watts rating of Inverters and battery banks. Several simulated arrays are connected in series and parallel combination to implement an array of panel. We can program the PIC microcontroller at any time using Mikro C with different environment condition.

6.2 FUTURE SCOPE

We will improve the simulation by using Data acquisition system integrated with Simulink. I want to implement multiple panel of PV modules with different type of variables like temperature, Irradiation, series and shunt connection of solar cell and other environmental parameter. I also want to test the large rating inverter with and without the connection of grid. Grid connected inverter can be tested with programmable photo voltaic Emulator. I want to improve the power supply by designing of converter using Power Electronics and also want to use different control strategies.

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APPENDIX 1

MICRO C PROGRAM FOR PIC 18F4520 MICROCONTROLLER

unsigned int Temp ;

unsigned int Volt;

unsigned int irradi;

void init()

{

CMCON=0x07;

TRISA=0xFF;

ADCON0=0x0B; //using for temp pin AN2//

TRISB=0X00;

ADCON0=0x0F; //using for Volt pin AN3//

ADCON0=0x07; //using for irradi pin AN1//

```
PORTB=0X00;
```

```
}
```

```
unsigned int TaC,K0,TaK,I11,I,I01,I0,Xv,dVdI_Voc,Rs,Vt-Ta,Vc,Ia;
```

```
unsigned int k,q,n,Vg,Ns,T1,Voc1,Icc1,T2,Voc2,Icc2,j;
```

```
void main()
```

```
{
```

```
int range[9]={400,550,675,800,895,900,800,500,350};
```

```
int tim=0,irrad=0;
```

```
void init();
```

```
if(tim=>07:00:00 && tim<08:00:00)
```

```
{
```

```
irrad=range[0];
```

```
}
```

```
else if(tim=>08:00:00 && tim<09:00:00)
```

```
{
```

```
irrad=range[1];
```

```
}
```

```
else if(tim=>09:00:00 && tim<10:00:00)
```

```
{
```

```
irrad=range[2];
```

```
}
```

```
else if(tim=>10:00:00 && tim<11:00:00)
```

```
{  
  
  irrads=range[3];  
  
}  
  
else if(tim=>11:00:00 && tim<12:00:00)  
  
{  
  
  irrads=range[4];  
  
}  
  
else if(tim=>12:00:00 && tim<13:00:00)  
  
{  
  
  irrads=range[5];  
  
}  
  
else if(tim=>13:00:00 && tim<14:00:00)  
  
{  
  
  irrads=range[6];  
  
}  
  
else if(tim=>14:00:00 && tim<15:00:00)  
  
{  
  
  irrads=range[7];  
  
}  
  
else if(tim=>15:00:00 && tim<16:00:00)  
  
{  
  
  irrads=range[8];  
  
}
```

```

else if(tim=>16:00:00 && tim<17:00:00)
{
    irrad=range[9];
}

Temp=ADC_Read(0);

Volt=ADC_Read(1);

irrad=ADC_Read(2);

k=(138*exp(-23))/100;

q=(160*exp(-19))/100;

n=12/10;

Vg=112/100;

Ns=36;

T1=273+25;

Voc1=2106/(100*Ns);

Icc1=380/100;

T2=273+35;

Voc2=1705/(100*Ns);

Icc2=392/100;

TaK=273+Temp;

K0=(Icc2-Icc1)/(T2-T1);

I1=Icc1*1000/*irrad*/ ;

I=I1+K0*(TaK-T1);

```

$$I01=Icc1/(\exp(q*Voc1/(n*k*T1))-1);$$

$$I0=I01*((TaK/T1)^(3/n))*\exp(-q*Vg*((1/TaK)-(1/T1))/(n*k));$$

$$Xv=I01*q/(n*k*T1)*\exp(q*Voc1/(n*k*T1));$$

$$dVdI_Voc=-115/(100*Ns/2);$$

$$Rs=-dVdI_Voc-1/Xv;$$

$$Vt_Ta=n*k*TaK/q;$$

$$Vc=volt/Ns;$$

$$Ia=0;$$

for (j=1;j<6;j++)

{

$$Ia=Ia-(I1-Ia-I0*(\exp((Vc+Ia*Rs)/Vt_Ta)-1))/(-1-(I0*(\exp((Vc+Ia*Rs)/Vt_Ta)-1))*Rs/Vt_Ta);$$

}

$$PORTB=Ia;$$

}