MODELLING OF PHOTOVOLTAIC ARRAY MONITORING SYSTEM

A DISSERTATION

Submitted in partial fulfilment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With specialization in Electric Drives and Power Electronics)

By

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MAY, 2016

CANDIDATE'S DECLERATION

I, hereby, certify that the work which is being presented in the dissertation entitled "**MODELLING OF PHOTOVOLTAIC CELL ARRAY MONITORING SYSTEM**" in the partial fulfillment of the requirement of award of degree of **Master of Technology** with specialization in **Electric Drives and Power Electronics** in **Electrical Engineering** and submitted in the **Department of Electrical Engineering of Indian Institute of Technology Roorkee**, is an authentic record of my own work carried out during a period of June, 2015 to May, 2016 under the supervision of **Dr. G.K. Singh**, Department of Electrical Engineering, IIT Roorkee.

The matter embodies in this dissertation has not been submitted by me for the award of any other degree of this or any other institution.

Date: 23rd May, 2016

Place: Roorkee **MANISH TIWARI**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ACKNOWLEDGEMENT

This Thesis is the result of the project **“Modelling of Photovoltaic Array Monitoring System”** for the partial fulfillment of Degree of Master of Technology with specialization in Power Electronics in Electrical Engineering. I wish to affirm my deep sense of gratitude to my guide **Dr. G.K. Singh**, Professor, Department of Electrical Engineering, IIT Roorkee for intuitive and meticulous guidance in completion of this report.

I convey my gratitude to **Dr. S.P. Srivastava**, Head of Department, Department of Electrical Engineering, IIT Roorkee, for providing me this opportunity to undertake this project.

I am thankful to **Dr. Avik Bhattacharya**, Assistant Professor, Department of Electrical Engineering, O.C. dissertation for evaluating the progress of our dissertation work and suggesting valuable changes to all students.

I also want to express my profound gratitude to all faculty members of EDPE, my friends for their motivation and co-operation throughout the work.

Last but not the least; I also acknowledge the blessings of my parents for encouraging me and giving moral support rendered to me throughout my life.

ABSTRACT

This dissertation comprises the process of monitoring the performance of solar panel with the application of MPPT under different meteorological conditions, buck boost converter and a non-ideal condition of **partial shading** of PV panel. It describes the elementary information of the simulation of solar panel taking Irradiance and temperature as input to work at different operating point. It includes two methods for applying MPPT technique i.e. **Perturb and Observe** and **Incremental Conductance**. These techniques are incorporated with a standalone PV system which comprises **DC-DC Buck boost converter** and **PWM based Inverter**, to track the maximum power of the PV panel.

The rest part of this work describes the functioning of monitoring system by collecting the data in different meteorological conditions. Analysis works are done for a chosen PV panel with specified Voltage, current and power rating. P-V and I-V characteristics of the panel are obtained at varying irradiance with constant temperature and vice versa. The partial shading condition which is not responded by perturb and observe, is addressed using incremental conductance algorithm. The simulation results show the output voltage, current and power at input and output side of DC-DC converter at different values of irradiance and temperature. Simulation results are needed to be analyzed to provide some meaningful information extracted by some statistical approach. There are statistical tools like **Monte Carlo simulation**, **regression analysis**, **curve fitting** etc. are available to fetch reliable information from the available set of data.

All these methods are meant to tell the health of the system at any point of time in online condition. And such monitoring is named in this dissertation as **condition monitoring** of the photovoltaic system.

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CHAPTER 1

INTRODUCTION AND REVIEW

1.1. INTRODUCTION

Traditional sources of energy that light up our homes today are coupled with alarming levels of pollution, global warming and ever increasing costs. This had propelled scientists across the globe to look for renewable energy sources that are non-polluting and more economical. The demand for clean renewable energy had prompted widespread research in the field of solar cell technology and its application. And this was how the solar cell technology evolved. The solar cell is an electrical device which converts the solar energy to electrical energy due to the photovoltaic effect. The first solar cell was made of silicon in 1954. During 1980's, the first solar power station was built in California with the capacity of 1MW. With the passage of time this technology thrived and started being used many applications like water heating, battery charging, and electricity production for households to satellites etc. In 2010, the world's total production of solar power reached to 40 GW and in 2011 it was 70 GW. These figures clearly lead the solar cell technology to brand a simple and promising renewable energy source.

Today renewable energy sources are the need of hour. This excessive demand has caused many researchers and industry to address the drawbacks and to look for the new possibilities in this field. According to a survey, the average performance ratio of PV system, in 1980, was .65 and therefore the echo for the requirement of monitoring system for PV panel raised. And this led to a great improvement in performance of PV system. According to a survey, done in 2010 in different part of the world, the average performance ratio of PV system has increased up to 0.85. ***The objective of monitoring is to improve the operation, reliability and, in turn, electrical and economic output of PV system.***

There are many factors like solar irradiance, temperature of panel, wind speed, dust and other abnormalities like partial shading, orientation of cell etc. affects the performance of PV panel. **The temperature and solar irradiance are the common parameters observed by monitoring systems**. The deviation of temperature or solar irradiance on PV array changes all PV array parameters and directly affect the energy produced by a PV system. The monitoring system associated with the solar panel keeps tracking the variation in the energy produced by the solar panel in different operating conditions and brings the system back to the point of maximum power yield. Moreover, it shows many trends in identifying the design flaws and accessing the performance analysis of the PV system.

This report consists of the designing of solar panel and buck boost converter along with the application of two MPPT methods: **Perturb and Observe, Incremental conductance** which provides the varying duty cycle value with change in operating conditions to make the solar panel work at maximum power point. And that fulfils the need of a mathematical model which is modelled to be monitored. The next stage is to monitor the solar array which is done by a technique i.e. regression modelling of performance model of PV system. In this technique, the performance of PV cell array is observed at different operating meteorological conditions to get actual power measurement and then being compared with the predicted values of the system parameters. The discrepancies and similarities etc. are shown in a way which depicts the overall performance and the design flaws of the existing system. It gives the idea to optimize the design and performance of PV system. Apart from temperature and irradiance variation, one of the most common problem metro cities, that is, Partial Shading is also discussed. A schematic diagram of PV system connected to grid is also presented in fig 1.

1.1.1. Objective of monitoring

- To measure energy yield
- To access PV system performance
- To quickly identify design flaws
- Improving reliability and service life of PV module
- Monitoring system can allow timely detection of operational performances and thus warranting a higher final energy yield than would be possible without monitoring. The detailed monitoring include an automatic dedicated data acquisition system with minimal set of parameters to be monitored.

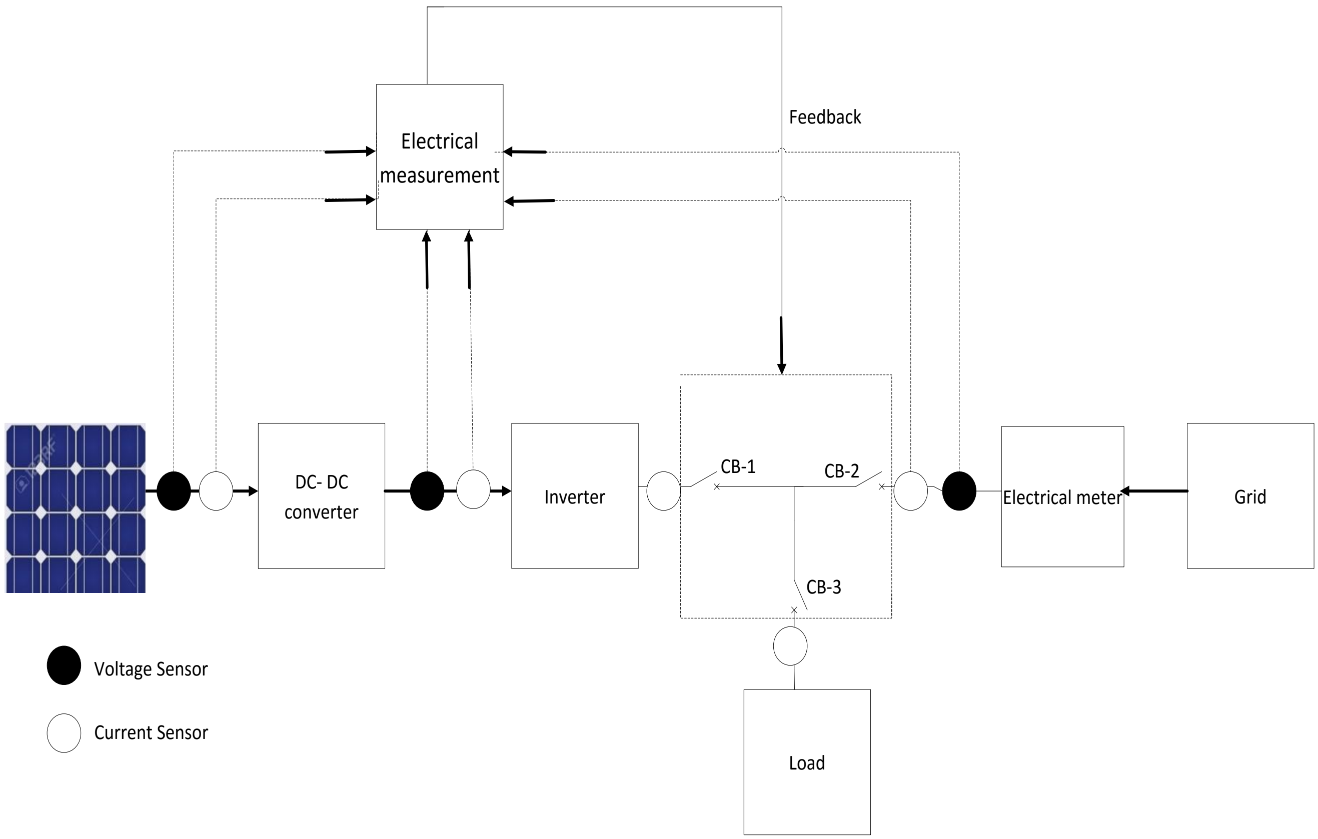


Fig. 1: Schematic diagram of PV system connected to Grid

1.2. Literature Review

- Huan-Liang Tsai in [13] explained the generalized simulation model of PV module using Simulink and analyses the performance of PV module with power electronic devices using Maximum power point tracking.
- Trishan Esram, Patrick L. Chapman in [12] provide a detailed information of various MPPT techniques algorithm and there comparison on the basis of effectiveness, popularity, complexity in implementation, speed etc.
- Athimulam Kalirasu, Subharenshu Sekar Dash in [19] gave a detailed simulation model of closed loop Buck Boost converter and how to find out the value of inductance and capacitance in design process.
- Texas Instrument [3], nice explanation of designing of Buck Boost converter.

- Saad Mekhilef, Rasoul Rahmani in [24] explained the concept of partial shading and its impact on the performance of PV converter. It suggests the strategies to tackle the problem of hotspot that may come due to the partial shading of PV panel.
- M. Torres, F.J. Munoz in [21] presented the concept of Monitoring system and explained the hardware set up to implement a physical monitoring system in consistent with the existing PV system.
- Hussein, K. H. Muta, Hoshino, M. Osakada in [18] gives nice explanation of application of MPPT techniques under rapidly changing operating conditions i.e. irradiance and temperature.
- Achim Woyte, Mauricio Richter, David Moser, Stefan Mau in [23] give critical analysis of why there is the need of monitoring system for PV system. They give a statistical data of performance of PV system across the world operating with and without monitoring system.
- Nicola Femia, G. Petrone, in [11] presented the explanation of Perturb and Observe mechanism under varying atmospheric conditions and its limitation of not able to respond in certain non-ideal conditions.
- K. Kobayashi, I. Takano, and Y. Sawada in [8] explains a fast and more sophisticated two stage Maximum power point tracking control algorithm for the non-ideal conditions such as Partial shading etc.

1.3. Organization of Report

Chapter 1 gives a brief introduction of what this report consists of. It explains the modern day's emphasis on renewable energy resources and the importance and penetration of the solar power system in addressing the need of clean energy. And since there is significant involvement of PV system in power supply to grid, there is need to continuously monitor the system. This chapter gives idea on what is Monitoring system and why it is important for PV system.

Chapter 2 gives the introduction of solar cell technology, its principle of conversion of solar power into electrical power and equivalent circuit. P-V, and I-V characteristics under varying irradiance and temperature are explained in this chapter. Performance Ratio of a PV power plant is also defined in this chapter.

Chapter 3 explains DC-DC converter, its working principle, and Buck Boost type of topology is explained in that. Moreover, it includes the steady state analysis of this converter with useful equations pertaining to the functioning of circuit and design values of inductor and capacitor.

Chapter 4 gives the introduction of MPPT and how this technology is useful in drawing the maximum power from PV panel. It also discusses the algorithm involved in MPPT P&O and Incremental conductance. This chapter explains the partial shading phenomena and the other conditions which hamper the performance of PV system.

Chapter 5 throws light on PV array monitoring system. It explains the need and objectives monitoring. What are the various techniques to monitor which were previously adopted and what is the present trend and requirement of the monitoring system etc. are discussed in this chapter briefly.

Chapter 6 explains the Simulink model of stand-alone PV system connected with Buck Boost converter having resistive load. This gives the results of PV system output and comparison of PV system output and converter output under variable irradiance and temperature conditions while operating with and without MPPT.

CHAPTER 2

PHOTOVOLTAIC SYSTEM

2. SOLAR CELL PRINCIPLE

The working principle of solar cell is based upon the ***Photovoltaic Effect*** due to which the solar energy is converted into electrical energy in solar cell. The photoelectric effect states that whenever sun light falls on the semiconductor surface, a part of this energy is absorbed by the electrons nearby the surface and they ejects from their valence band to conduction band and this freely moving energized non thermal electron reaches nearby junction of the two diffused N- type and P-type material where they are accelerated into another material by a built-in potential as seen in the figure 2.1. This generates an electromotive force which in turn converts the solar energy into electrical energy and generates the current in closed path.

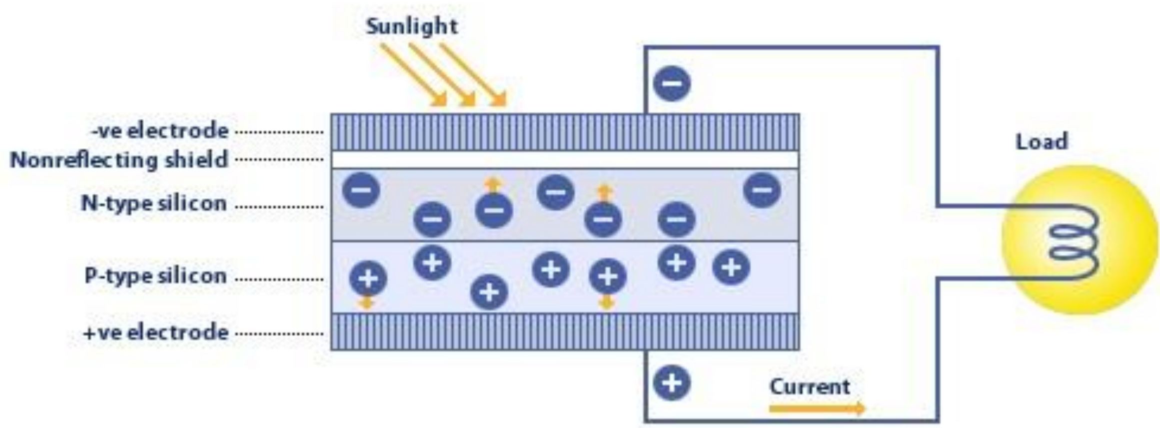


Fig. 2.1Photovoltaic effect in Solar Cell

2.1.1. Material and Rating

Generally, the semiconductor materials like ***Silicon*** (Si) or the alloy like ***Cadmium telluride*** are used for manufacturing the solar cell. On the basis of material used, the photovoltaic solar panels are Single crystalline, Polycrystalline, String Ribbon, Thin Film type etc.

The maximum output voltage of a single cell is 0.7 volts. For application purpose, these cells are used in combination of series and parallel connections. Series string of a PV cells gives additive voltage of all cells while parallel string allows more current to flow. The PV panel generally have the DC power rating varying from 100W to 350W. 1000W/m2 irradiance and 25°C are referred as the standard test conditions. The characteristics of a solar cell include…

Pm: Maximum power

Voc: Open circuit voltage

Isc: Short circuit current

Imp: Maximum power current

Vmp: Maximum power voltage

PV Module

A PV module consists of many PV cells wired in parallel to increase current and in series to produce a higher voltage. 36 cell modules are the industry standard for large power production.

PV Array

A PV Array consists of a number of individual PV modules or panels that have been wired together in a series and/or parallel to deliver the voltage and amperage a particular system requires. An array can be as small as a single pair of modules, or large enough to cover acres.

2.2. Equivalent Circuit

A simplest equivalent circuit of a solar cell is a current source in parallel with a diode. As shown in the figure 2.2, the solar cell is approximated as a current source Iph i.e. photocurrent. The value of Iph depends upon the solar power incident on the solar cell. A diode is connected in parallel to identify the non-linearity of a solar current to losses in the recombination of electrons and holes i.e. ***reverse saturation current I_d.*** Rs and Rsh represents the losses incurred by the conductors. Ideally, Rs=0 and Rsh = inf i.e. no leakage current to ground. Typically, in a silicon cell of high quality of one square inch, series resistance is about 0.05 to 0.1 ohm and shunt resistance is about 200 to 300 ohms. Output current of cell is the function of photodiode current, reverse saturation current, Rs, Rsh, temperature.

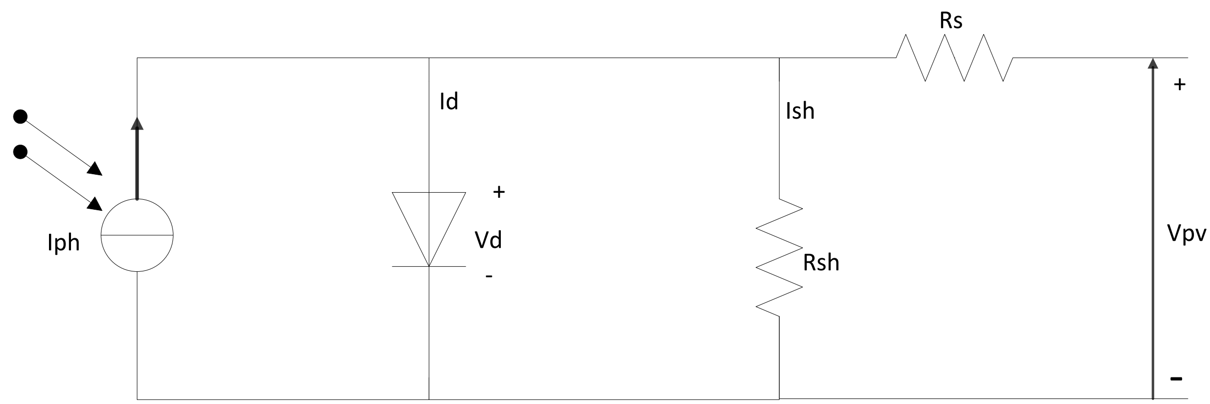


Fig 2.2. Equivalent circuit of solar cell

$$I = I1g - Ios * \left[exp\left\{q * \frac{V+I*Rs}{A*k*T}\right\} - 1\right] - \frac{V+I*Rs}{Rsh} \tag{2.1}$$

Where,

$$Ios = Ior * \left(\frac{T}{Tr}\right)^2 [exp\{q * Ego\}]$$

$$I1g = \{Iscr + Ki * (T - 25)\} * lambda$$

I & V: Cell current and voltage

Ios: Reverse saturation current (A)

I1g: Photon current (A)

T: PV cell operating temperature (°C)

K: Boltzmann's constant ($1.38*10^{-23}$ J/K)

q: Electron charge ($1.6*10^{-19}$ C)

K1: Temperature coefficient of the short circuit current (A/°K)

S: operating solar radiation (W/m^2)

Isc: Short circuit current at STC (A)

Ego: Bandgap energy of the semiconductor (J)

A: Ideality constant (Between 1 and 2)

Tr: PV cell absolute temperature at STC

Iscr: PV cell's reverse saturation current at temperature Tr (A)

Rsh: PV cell intrinsic parallel resistance

Rs: PV cell intrinsic series resistance

Equation for Ns cell in series and Np cell in parallel,

$$I = Np * I_{lg} - Np * I_{os}\left[exp\left\{q * \frac{\frac{V}{N_S}+I*\frac{R_S}{N_P}}{A*k*T}\right\} - 1\right] - \frac{V*\frac{N_P}{N_S}}{R_{sh}} + I * \frac{R_S}{R_{sh}} \quad (2.2)$$

2.3. PV Array Characteristic

P-V and I-V characteristic of a PV array are the most important characteristics. PV array has a specific P-V and I-V characteristic for a particular irradiance and temperature. The solar power system acts as a current source whose current increases as the irradiance increases and temperature decreases. As seen in figure 2.3 and 2.4, the MPP is at the knee bent of the I-V curve and corresponding global maxima of P-V curve.

In I-V curve, the current remains constant at Isc for a while and bends at the knee point which is called 'Maximum Power Point' and finally reaches the Voc. As temperature rises, this knee point shifts to the left indicating lesser output power. Whereas, in P-V curve, power rises exponentially and drops down at MPP. As irradiance decreases, peak shifts downward which shows that power output is decreasing.

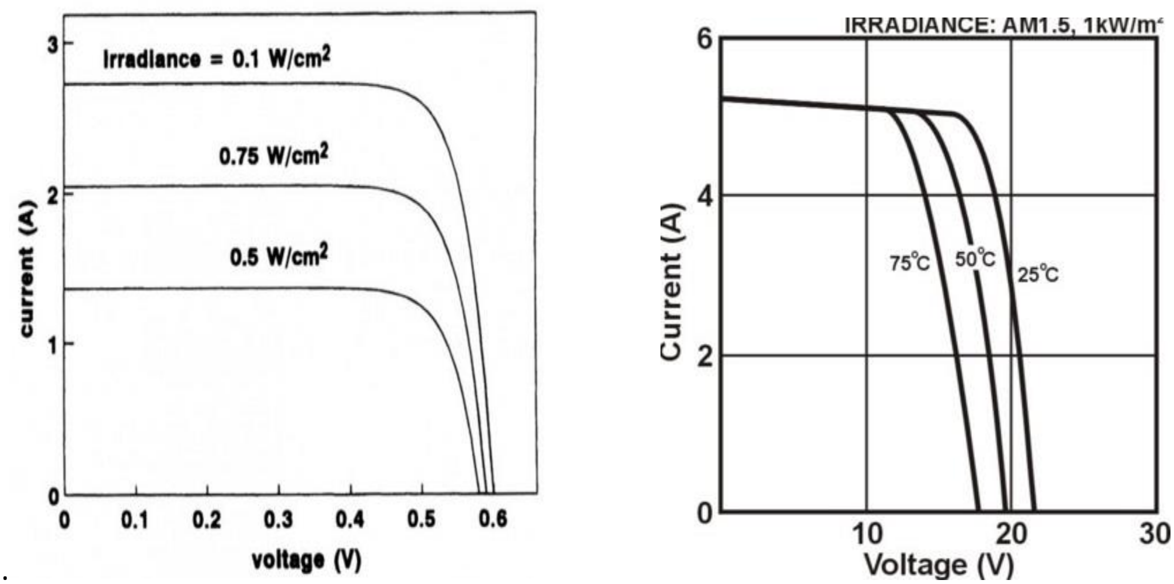


Fig 2.3: I-V characteristic of varying Irradiance (G) and Temperature (T)

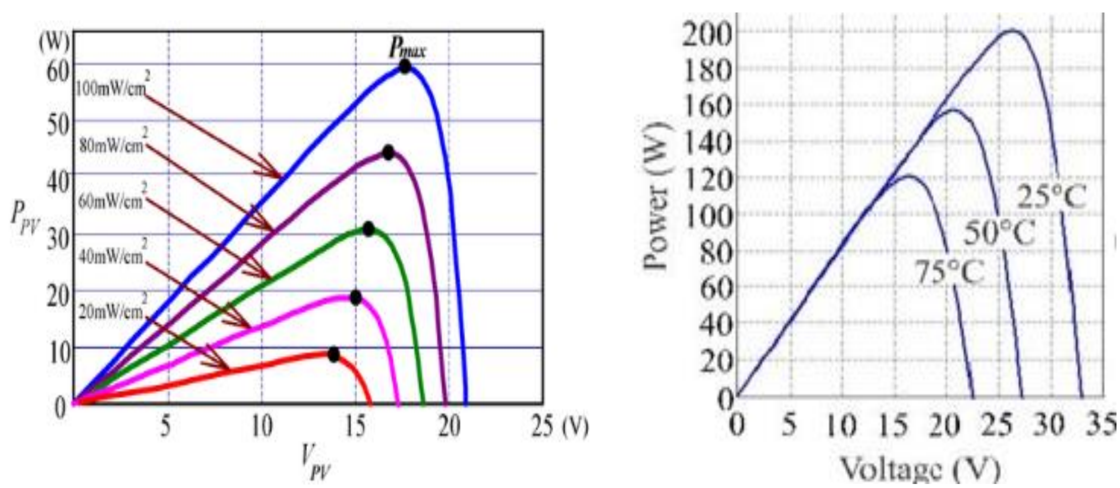


Fig 2.4: P-V characteristic of varying Irradiance (G) and Temperature (T)

2.4. Performance Ratio (PR) and Loss Factor

Performance ratio is the most important aspect to be measured for evaluating the overall behavior of PV plant. PV system performance depends upon many parameters like location, the climate and several losses.

$$PR = \frac{Final\ Energy\ Yield}{Reference\ Energy\ Yield}$$

Where,

$$Final\ Yield = \frac{Daily\ Load\ Consumption}{Peak\ Installed\ Capacity}$$

2.5. Trend in PV system performance

It is observed that with the advent of PV system in 1950s, the performance ratio had increased from 0.5 to 0.65 in late 1980s and 0.65 to 0.7 in 1990s and to more than 0.8 nowadays. Early PV system were not able to generate the expected energy yield due to some constraints in installations of DC system with poor reliability and bad MPP tracking of inverters, long repairing times and shading problem. In studies performed under IEA PVPS Task 2 PV systems in 11 countries were analyzed during eight years of installation. In a study performed in year 2000, 70 grid connected PV system were analyzed, where annual energy yield (Yf) was found to fluctuate only slightly from one year to another. It was found that well maintained PV systems show PR value 0.72. While the PV system installed before 1995 show the average PR value of 0.65. It was analyzed that this increment in the PV system PR came due to higher component efficiency, greater reliability of PV system. Later in many studies it was found that the new system were providing better performance with greater reliability.

Finally a study performed in 2012, the PR of about 100 German PV system installations were investigated and it was found that the in case of German PV systems good performance were above 0.84 and some PV systems which showed PR value around 0.75 they were actually affected by shading, bad inverter performance etc.. On the other hand, the systems with better efficiency and a separate performance monitoring showed PR very close to 0.9. And, hence, proved the necessity of Monitoring and analyzing the performance of PV system.

CHAPTER 3

DC-DC CONVERTER

3.1. INTRODUCTION

A **DC**-to-**DC converter** is an electronic circuit which converts a source of direct current (**DC**) from one voltage level to another. There are basically three topologies which are very popular and used most commonly i.e.

- Buck Topology
- Boost Topology
- Buck Boost Topology

All three topologies are different on the basis of connection of inductor, capacitor, diode and controlled switch etc. there are some basic properties associated with each of these topologies which include output to input voltage ratio in steady state, output to input current ripple, output voltage ripple. Transfer function of converter shows the ratio of output voltage to duty cycle. Depending upon the requirement of output voltage etc. topologies are chosen. Here, Buck boost topology of converter is described.

3.2. Buck Boost Topology

This converter is having a unique ability to step up or step down the output voltage in magnitude. In other words, it has both a buck and a boost in just one configuration. The output voltage produced can vary from much higher magnitude to almost zero. And that is why Buck boost converter is chosen for this scheme.

3.2.1. Principle of Operation

It is based on the principle that

When the switch is ON, energy gets accumulated in the inductor, as the input voltage source gets

Connected directly to the inductor. Also, when this happens, the energy to the output load is supplied by the capacitor.

Now when the switch is turned off, the inductor gets connected directly to the load and capacitor, so the energy is transferred from the inductor to the capacitor and output load (resistive).

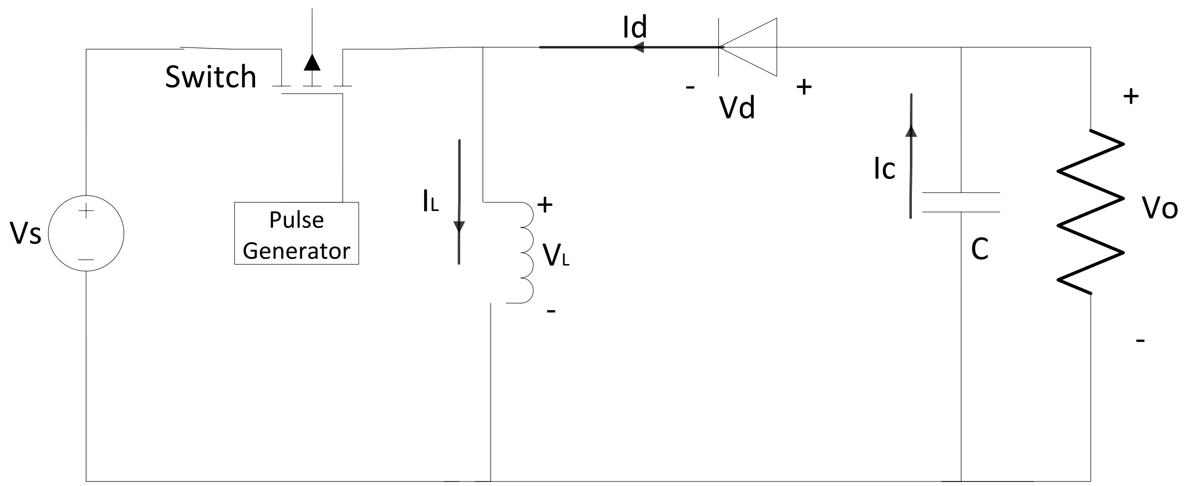


Fig. 3.1: Buck Boost equivalent circuit

3.2.2. Steady State Analysis for Continuous Conduction Mode

The combination of MOSFET and DIODE makes a facility of single pole double throw (SPDT) switch. And therefore two conditions arises i.e. when inductor (L) is connected to source (Vs) and the other one is when Inductor (L) is connected to load.

Case 1.

When switch is **CLOSED,**

In that case inductor gets directly connected to the source,

$$v_L = V_S$$

The rate of change of inductor current is a constant, indicating a linearly increasing Inductor current.

$$(\Delta i_L)_{closed} = (\frac{V_S\, DT}{L})$$

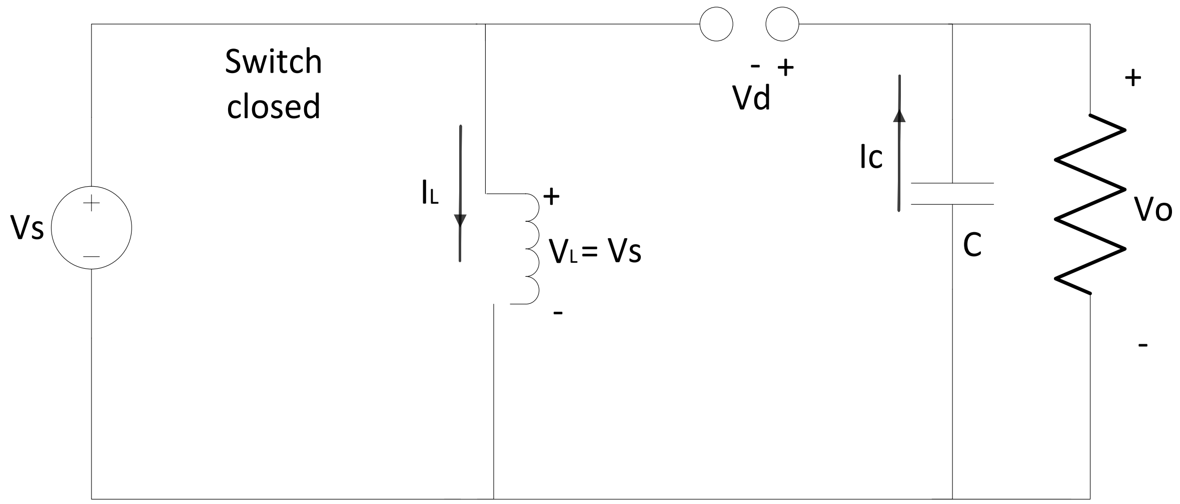


Fig. 3.2: equivalent circuit with switch **‘open’**

Case 2: When switch is **OPEN**,

When the switch is open, the current in the inductor cannot change instantaneously, resulting in a forward-biased diode and current into the resistor and capacitor. Load comes in parallel of charged Inductor. So voltage across inductor,

$$v_L = -V_0$$

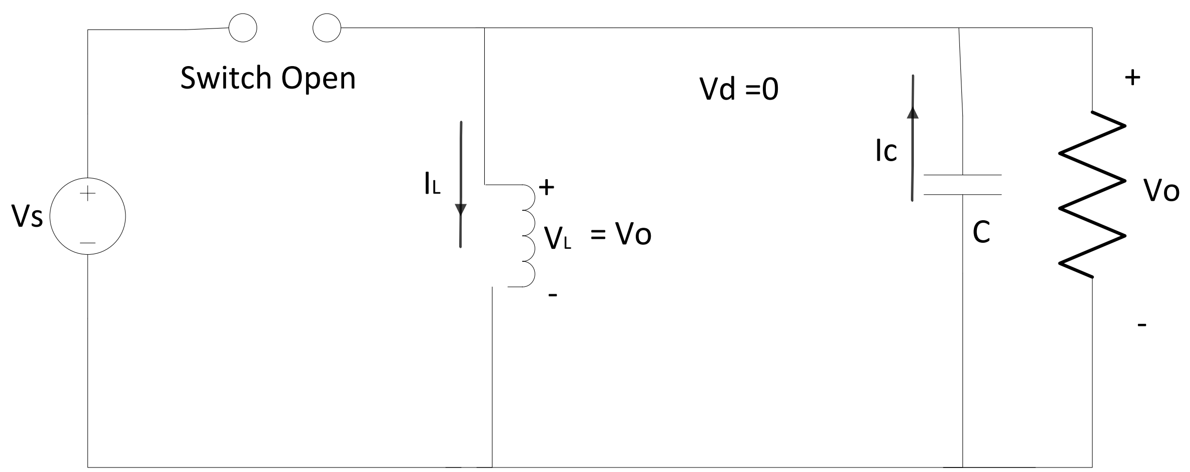


Fig. 3.3: equivalent circuit with switch **‘closed’**

Again, the rate of change of inductor current is constant, and the change in current is

$$(\Delta i_L)_{open} = \frac{V_0(1-D)}{L\,f}$$

The output voltage of Buck Boost is given by,

$$\boldsymbol{V_0} = -\left[\boldsymbol{V_S}\ \frac{\boldsymbol{D}}{(\boldsymbol{1-D})}\right] \qquad (3.1)$$

As shown in the above equation, the output voltage of Buck Boost converter is having reverse polarity. This can be disadvantageous in many applications. Moreover, the output voltage V_o is equal in magnitude with source voltage V_S at 0.5 duty cycle.

$$D = \frac{|V_0|}{|V_0|+V_S} \qquad (3.2)$$

As duty cycle (D) increases beyond 0.5, converter gives Boost operation i.e. step up while below 0.5, it provides Buck operation i.e. step down. Therefore, this circuit combines the capabilities of the buck and boost converters.

Note that the source is never connected directly to the load in the buck-boost converter. Energy is stored in the inductor when the switch is closed and transferred to the load when the switch is open. Hence, the buck-boost converter is also referred to as an *indirect* converter.

Power Balance: Power absorbed by the load must be the same as that supplied by the source,

i.e.

$$\frac{{V_0}^2}{R} = V_S * I_S$$

$$\frac{{V_0}^2}{R} = V_S * \mathrm{I}_L * D$$

$$\mathrm{I}_L = \frac{V_S * D}{R(1-D)^2}$$

Maximum (I_{max}) and minimum (I_{min}) inductor currents,

$$I_{max} = \mathrm{I}_L + \frac{\Delta i_L}{2}$$

$$I_{max} = \left[\frac{V_S * D}{R(1-D)^2} + \frac{V_S\,DT}{L}\right] \qquad (3.3)$$

$$I_{min} = \left[\frac{V_S * D}{R(1-D)^2} - \frac{V_S\, DT}{L} \right] \tag{3.4}$$

For continuous current, the inductor current must remain positive. To determine the boundary between continuous and discontinuous current, *I*min is set to zero that gives,

$$\boldsymbol{L_{min}} = \left[\frac{\boldsymbol{V_S * D}}{\Delta \boldsymbol{i_L * f}}\right] = \left[\frac{\boldsymbol{(1-D)^2 R}}{\boldsymbol{2\, f}}\right] \tag{3.5}$$

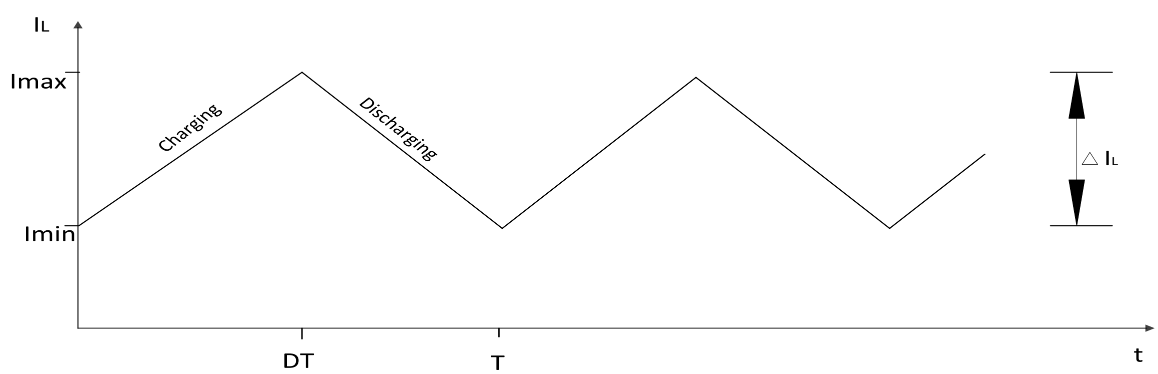
Output voltage ripple for the buck-boost converter is given by,

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf} \tag{3.6}$$

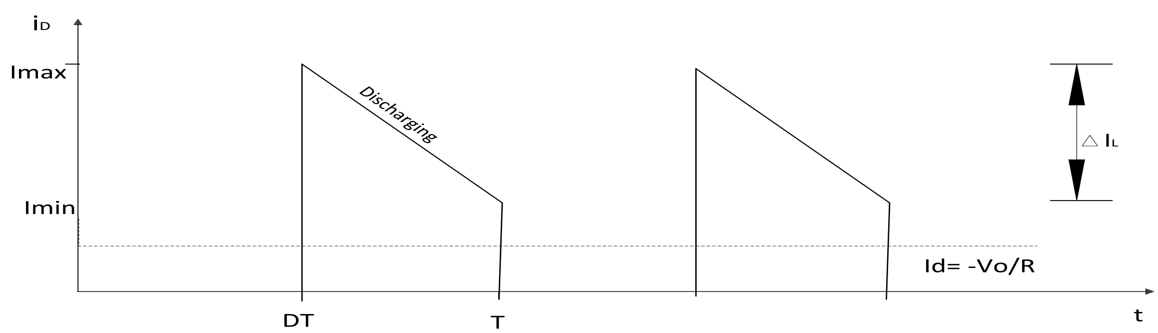
So the minimum capacitance value required will be

$$\boldsymbol{C_{min}} = \frac{\boldsymbol{D}}{\frac{\Delta \boldsymbol{V_o}}{\boldsymbol{V_o}} \boldsymbol{* R * f}} \tag{3.7}$$

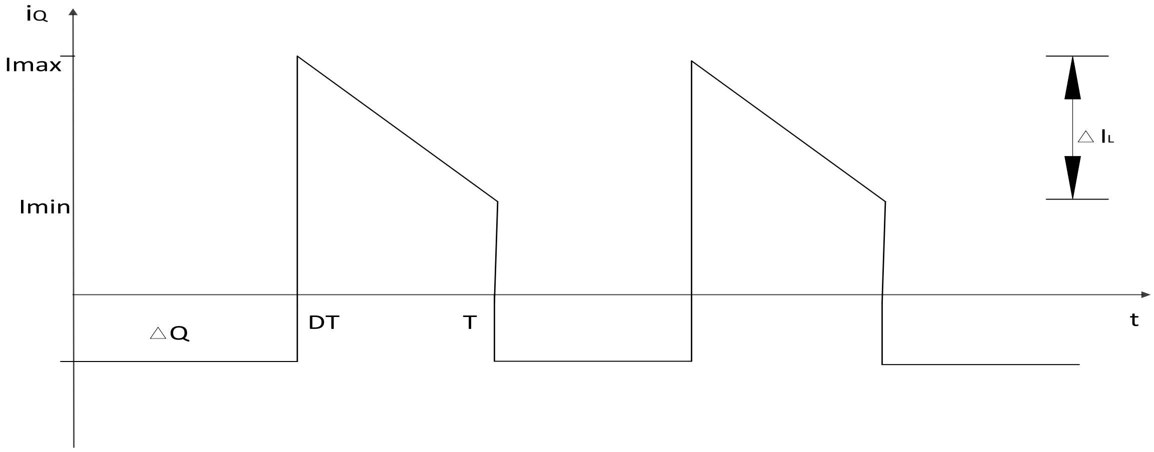
Waveforms in Continuous Conduction Mode,



(a)



(b)



(c)

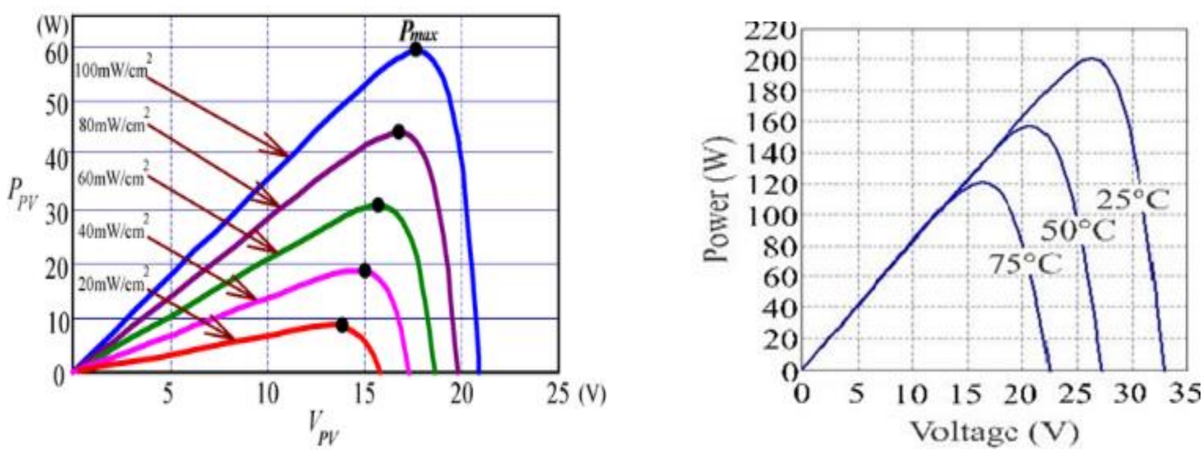
Fig. 3.4: (a), (b), and (c) are inductor current, load current and capacitor current waveforms

CHAPTER 4

MAXIMAM POWER POINT TRACKING

4.1. INTRODUCTION

Maximum power point tracking technique is used to operate the PV panel at its maximum power output yield while operating in different operating conditions. And thereby improves the performance and efficiency of the solar cell. The purpose of maximum power point tracking (MPPT) is to track the supply condition and adjusting duty cycle to determine load so that maximum power can be transferred. As we can see from the PV curve of solar panel shown in fig 4.1(a) and (b), the output power of solar panel reaches to maximum value at a certain voltage and current. That point is termed as the Maximum power point (MPP). In this technique, the operating point keeps on changing till it reaches the MPP. This approach of maximize power yield is applied at the input side and, therefore, it doesn't depend on the load applied at the output side. In fig 4.1(a), (b), it is clearly shown how the changes in the meteorological conditions such as irradiance and temperature changes the MPP.



(a) (b)

Fig. 4.1 (a) and (b) PV curve of solar panel with variable irradiance and temperature

4.2. MPPT Techniques

There are many MPPT methods [12] which have been developed and implemented. These methods vary in implementation in hardware, complexity, range of effectiveness, cost, ability to respond the partial shading and convergence speed. Incremental conductance, Perturb and Observe, Fractional open circuit voltage method, ANN, Fuzzy logic control, etc. are commonly used MPPT techniques. Two of these techniques are explained in this report.

4.2.1. Perturb and observe

P&O method of MPPT is based on the perturbation in the operating voltage of the PV array. In case of PV array, connected to a power converter, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Output Voltage (Vpv) and current (Ipv) are sensed continuously and corresponding output is calculated instantaneously. This instantaneous output is compared with the previous power output of PV system. The nature of error decides the direction of next perturbation. If this change in the power output comes positive then the subsequent perturbation will occur in the same direction or vice versa as given in table I. Once the current is known, it is varied at a constant rate. And this rate decides the rate of change in parameter i.e. duty cycle (D) in case of Buck-Boost converter. The whole algorithm of P & O is shown in fig 4.3.

This method of MPP tracking is the simplest one which can easily be used in simulation and microcontrollers. But some drawbacks are also associated with this technique. One of these drawbacks is the inability of P&O to respond in some abnormal conditions such as partial shading. Partial shading is a very common phenomena which affects the performance of the PV system. When one or more cells in one module are shaded, there comes several peaks in the PV curve. For such a curve P&O settles the operating point at some local maxima which may or may not be global maxima. Therefore, either modified P&O or some other technique is adopted for partial shading. Moreover, once the MPP is tracked by P&O, operating point oscillates around the MPP. It doesn’t settles down quickly which, in turn, causes loss of energy. In order to reduce these oscillations, perturbation step size can be minimized. However, reduction in perturbation size causes the slowing down of MPPT. This problem can be solved by having variable perturbation size that gets smaller nearby MPP.

P&O technique may fail to respond under rapidly varying atmospheric conditions as illustrated in Fig.4.2. Let point A be the operating point of PV system. Increase in irradiance shifts the PV curve from P1 to P2 within a sampling period and, therefore, operating point also moves from A to C. This shows an increase in power and voltage and that's why variation in duty cycle is kept in the same direction. Therefore, operating point oscillates about the maximum point and takes some to settle at that point.

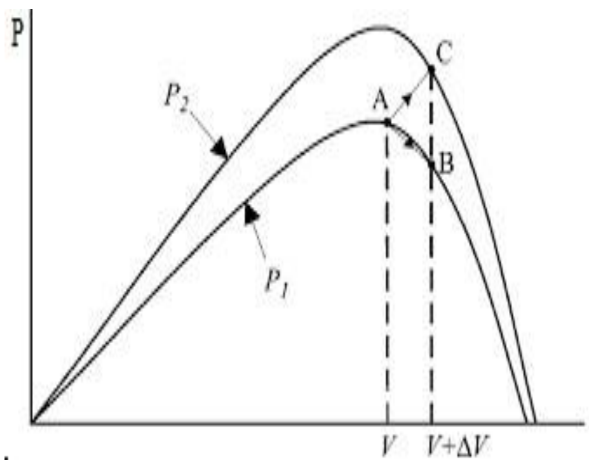


Fig. 4.2. Divergence of P & O from MPP

ΔPpv	ΔVpv	Duty cycle
>0	>0	Increment
>0	<0	Decrement
<0	>0	Decrement
<0	<0	Increment

Table 4.1: summary of P&O

4.2.2. Incremental Conductance

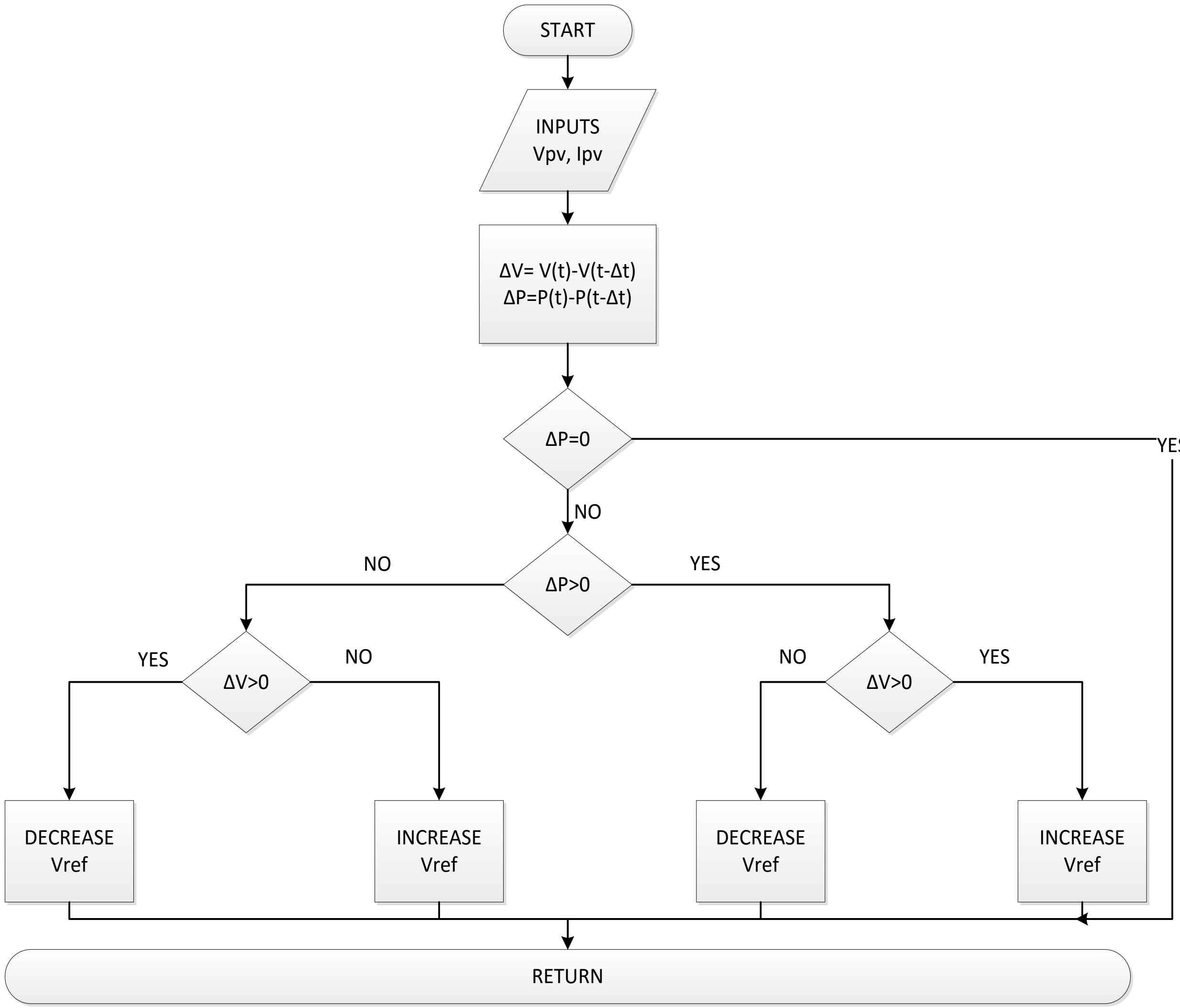
This MPPT technique works on the principle of maxima that at the peak point slope of the curve will be zero. On the left of the MPP, it is positive and negative at right side of MPP as given by in following table,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \sim = I + V\frac{\Delta I}{\Delta V} \tag{4.1}$$

At MPP	dP/dV=0	(ΔI/ΔV) = (-I/V)
On the left of MPP	dP/dV>0	(ΔI/ΔV) > (-I/V)
On the right of MPP	dP/dV<0	(ΔI/ΔV) < (-I/V)

Table 4.2: Summary of Incremental Conductance

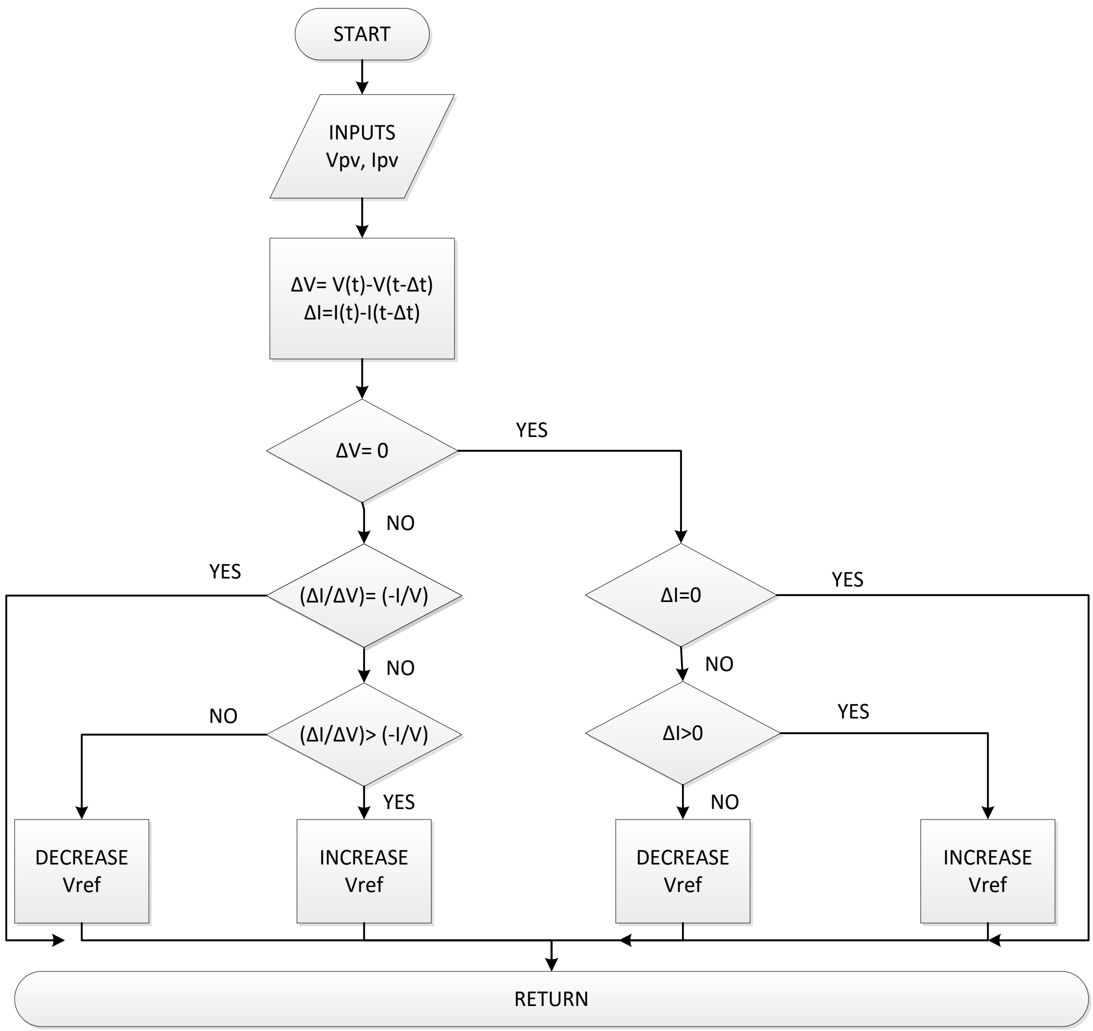
Here, in order to track the maximum power point, the instantaneous conductance is compared with the incremental conductance. As per the equation (4.1), as long as instantaneous conductance is equal to the incremental conductance, slope of the PV curve is zero which is the peak point of the curve. The proposed algorithm for incremental conductance is given in fig (4.4). Vref is the voltage at which the PV array is forced to operate. At the MPP, that Vref is nothing but the Vmpp. Let say PV array is working at MPP. The operation of the PV array is maintained at Vmpp unless there is a change noted in ΔI, indicating the change in atmospheric conditions as well as maximum power point. The algorithm then either decreases or increases the Vref to track the new MPP. It is the size of the increment which determines the speed of MPPT technique. Although it is possible to achieve fast tracking by setting bigger increments in Vref yet it is not suitable as it may cause the system more oscillatory about MPP.



PERTURB AND OBSERVE ALGORITHM

Fig. 4.3

The reason why incremental conductance is better technique than perturb and observe is that it can track MPP without much oscillations about maximum power point. Moreover, under the varying irradiance conditions, it can track maximum power point with better accuracy as compared to Perturb and Observe. It takes longer time to calculate maximum power point which is the drawback of the conventional incremental conductance.



INCREMENTAL CONDUCTANCE ALGORITHM

Fig 4.4

4.3. Effect of Non- ideal conditions on PV panel

4.3.1. Partial Shading Phenomena

Ideally PV panels are supposed to operate under fully radiated condition but, in reality, this is not the case. In residential areas, it is quite possible that due to obstruction of trees, poles, buildings etc. solar modules or panels may get shaded or partially shaded. In case of partial shading, system may get seriously affected.

To understand partial shading effect let us take the following example of three cells connected in series as shown in fig.4.5. Initially all three cells are equally radiated and generating a photo current (Iph). At certain point, the corresponding parallel diodes get forward biased and carry major portion of photo current. Voltage across load resistance = 3*Vd.

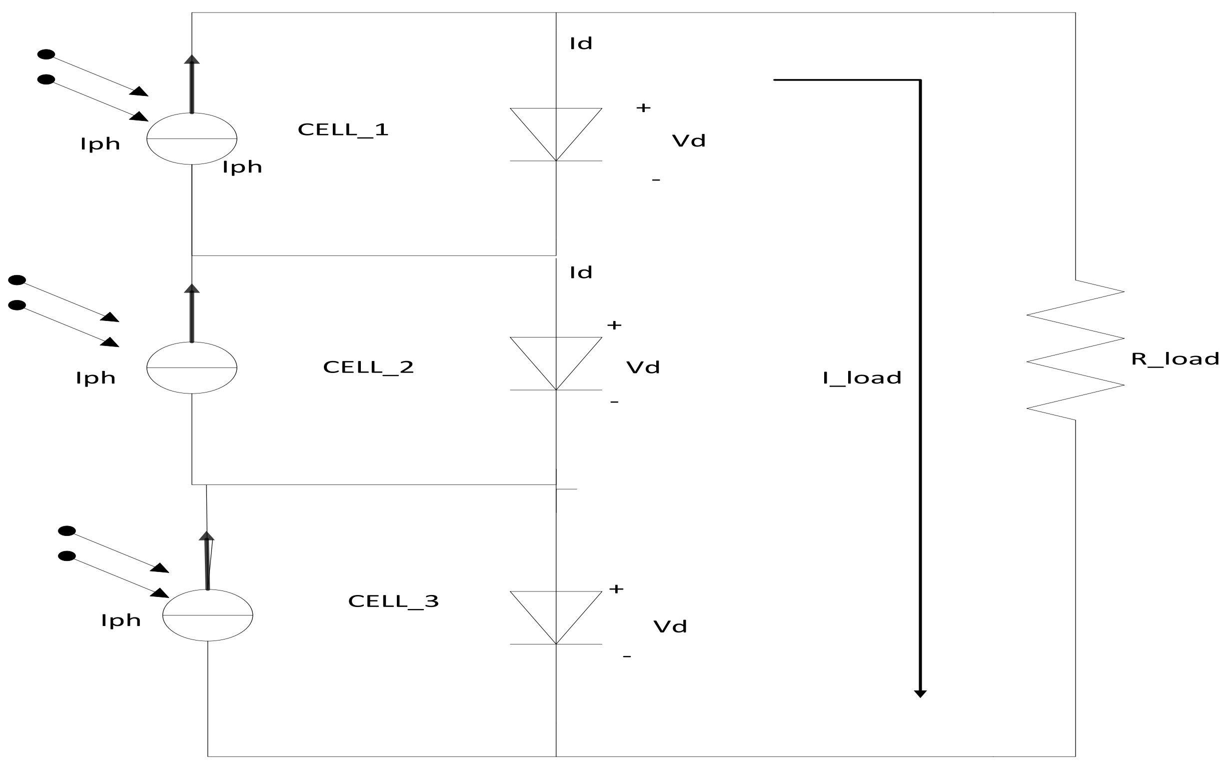


Fig. 4.5: three cell equivalent circuit connected in series

Now, in fig. , Cell_3 gets shaded producing Iph=0. While rest of the two still producing Iph causing cell_3 diode to get reverse biased. Voltage across load resistance = 0. If number of such series connected diodes are more then it will lead to a large reverse bias voltage across the diode that will cause its breakdown. This phenomena of breakdown of diode results in dissipation of energy which leads to the Hotspots. In order to protect the other cells from temperature rise and breakdown, connect an antiparallel diode named Bypass diode which allows the load current to flow and bypasses the Cell_3 diode.

n

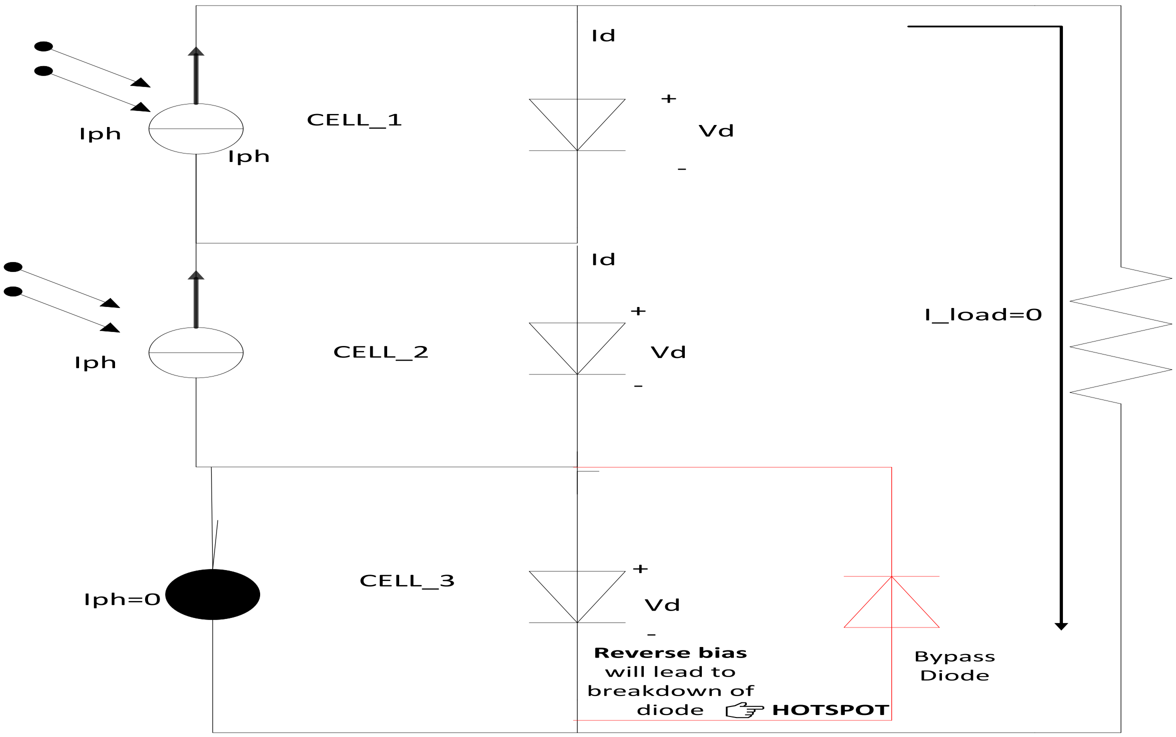
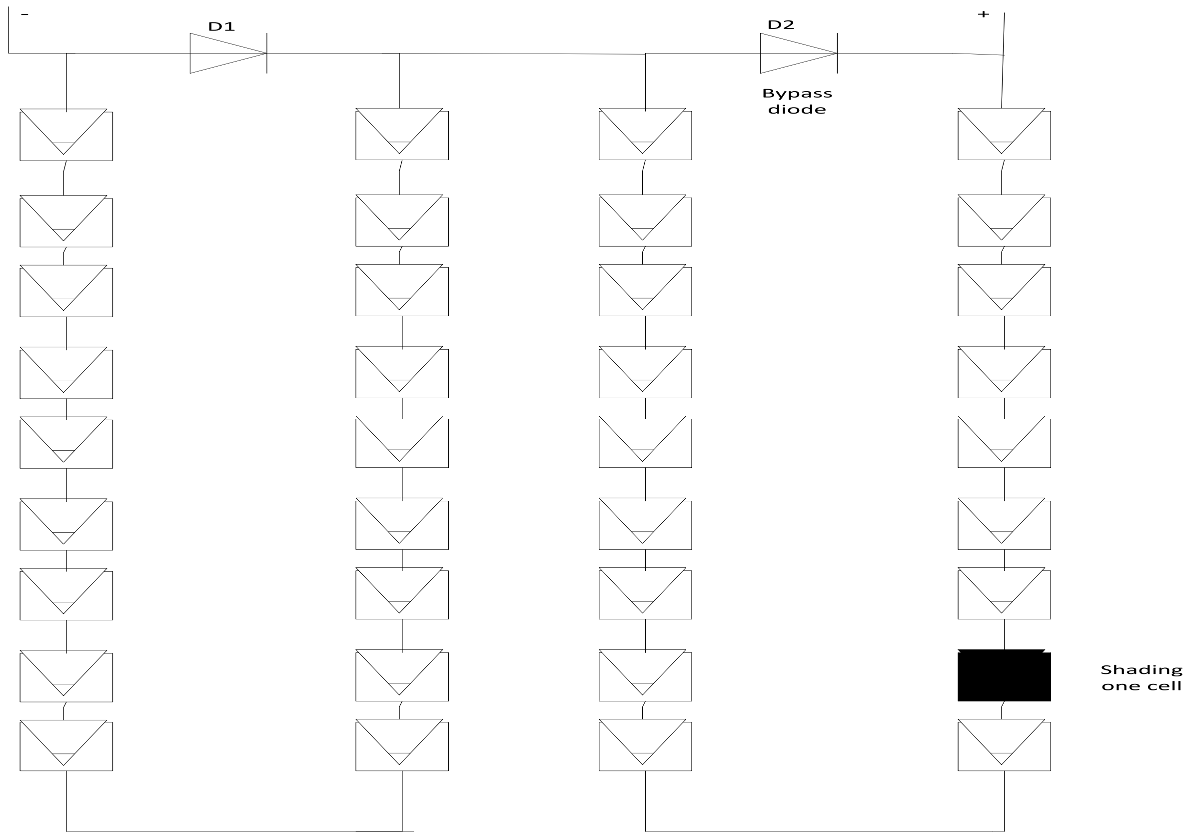


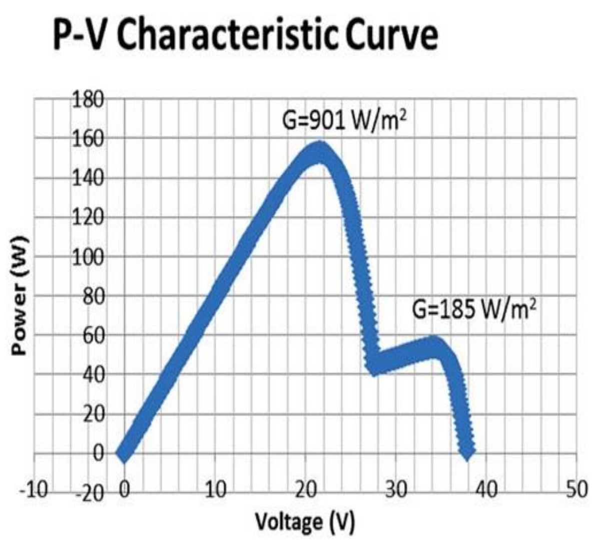
Fig.4.6: three cell connected in series with cell _3 shaded

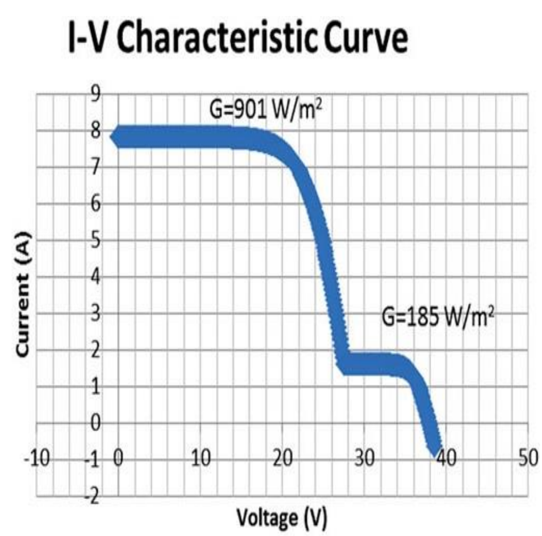
Example of an experiment on PV module with partial shading,

In an experiment shown in the figure used Kyocera solar KD140GH- 2PU at 61°C, 1.5 AM, 901 W/m2. Two solar module connected in series having 18 cells in one module. In one of the module one cell is shaded with 185 W/m2 as irradiance causing bypass diode D2 to short its group of cells, reducing the module voltage by half. The module diagram and accordingly P-V and I-V curves are shown in figure 4.7 (a),(b),(c).



(a)





(b) (c)

Fig. 4.7: (a) shaded module, (b) P-V characteristic, (c) I-V characteristic under partial shading

4.3.2. Cell temperature

For better productivity, the temperature of PV system should not exceed from the standard value for which system is modelled. As shown in the above mentioned figure 4.1(b), Open circuit voltage Voc is most affected by temperature. With increment in temperature, Isc remains constant while Voc decreases which causes fall in the peak of PV curve.

Effect of High Temperature

The ambient temperature of the surrounding in which solar panel is placed if changes, it affects the performance of the overall system. According to one case study done on the effect of high temperature, if the temperature goes up 20 degrees Celsius more than ambient temperature, it lowers down the overall efficiency of the panel. In an experiment done in UK, after 42 degree Celsius temperature, there comes a drop of 1.1% in efficiency with every 1 degree Celsius rise in temperature.

Effect of Low Temperature

Solar cell efficiency is better when the temperature is low. For PV panel to function efficiently, standard temperature and optimum insolation are essential conditions. Unfortunately, in most of the cold areas like nearby polar region, solar energy is not found in abundance. Generally, in all cold areas, atmosphere is snowy or cloudy for entire year. And, therefore, these area are not at all suitable for solar power generation. At most, solar panel can be tilted at certain angle to slide off the snow faster.

4.3.3. Solar Insolation

It is the measure of the amount of solar energy falling on per unit area per unit time. Not only temperature, it is the irradiance as well which influence the performance of solar system greatly. Change in irradiance doesn't affect Voc much but it influences Isc significantly as more irradiance means more number of electrons travelling from valence band to conduction band i.e. more photo current. And, therefore, the peak of PV curve rises upward.

Chapter 5

PV Monitoring system

5.1. Introduction

This chapter tells about PV system monitoring and its importance, different existing monitoring systems and discusses the required sub-systems at dc side of monitoring.

In general terms, a system monitor fetches some data from the given system and based on the analysis of the data gives some meaningful information as well as some corrective measures to optimize the existing system. ***It is just fine to monitor the PV system, not the core requirement of the system to be operational***.

5.2. Need for monitoring PV system

PV system performance is degraded by many factors such as soiling, shadowing, increased series resistance, Inverter faults, shunting and other component faults. It was observed that the overall output of the PV system is reduced by a significant amount of 18% annually due to these factors. Moreover, it reduces the overall life and performance of PV system. These concerns have, therefore, led to requirement of such an arrangement which can automatically supervise and monitor constantly the internal as well as external factors which affect the performance of PV system and in that way give the measures to rectify or minimize the problems associated with PV system specially small PV system where no specialized personnel is present at the site.

In 2012, IEA presented a report based on the case study done over the PV panel installed in Germany, which manifests that the PV panel which were installed before 1990 in different part of Germany with no monitoring system gave performance ratio of about 0.65 while with monitoring system, it was 0.85-0.9. This statistics emphasizes the need of the condition monitoring of PV system.

The purpose of monitoring is nothing but to maximum energy yield with minimum economic loss, to access the performance the system and timely finding out the malfunction and design flaws if any. This improvement in existing PV system cannot be achieved with continuously monitoring them on the field.

5.3. AC side monitoring

It is important to do monitoring on AC side of the inverter effectively in order to allow utility company to maintain the power quality, to get information about the imminent outages and to stick to the standards for connecting solar power system to grid.

5.3.1. Prevention of power outages

Unlike to the traditional fossil fuel based power system, the unconventional PV system depends upon the factors like solar irradiance, temperature, cloud cover etc. The output power of PV system drops or rises drastically depending upon these factors. Sudden drop in power output can cause power outages [28]. As PV system has become a significant source of power and penetrating into the grid, it is very important now to use a centralized monitoring system. Such a system will be able to contribute greater to the grid. If the monitored PV system is not able to supply power and its output reduces, the controllers will provide power to the grid from the additional systems such as diesel electric plant or battery storage.

5.3.2. Islanding Protection

Connection of the PV arrays with grid poses the safety risk which is known as Islanding. Islanding occurs when there comes a fault in wider grid and causes power outage, but PV doesn't switch off. This may result in power supplied by PV system to the local loads and making small 'island' in the grid. This island which is having energized wire pose threat to the life of the workers and technicians who are there to fix the faults. Most of the modern inverters are equipped with the facility of anti-islanding. Whenever the power outage occurs in the grid, this (anti-islanding) feature detects the fault and turns off the inverter [29]. In addition to this, PV companies provide a manual switch which connects PV system to grid. Whenever technician comes to fix the fault they first turn off the switch before beginning the work.

IEEE standard 1547 gives the guidelines for connecting a distributed generating resource (e.g. PV system) with electrical grid. These guidelines emphasize on the anti-islanding protection. PV system must be able to detect the abnormalities such as outages and in turn be able to cease the electric power output. Moreover it mandates that if the power at the point of common coupling (PCC) exceeds 250 KVA, provision to monitor the connection status, voltage and power output at PCC is must.

5.3.3. Power quality improvement

It is the responsibility of the power utility companies to ensure the power quality. A significant deviation in frequency, voltage, current magnitude and waveform results in the poor power quality.

The utility does not have any control over the amount of current which is drawn by the load but it does have concern with the quality of current being drawn. It is inevitable to keep voltage, frequency deviation in certain limits to maintain the power quality. The output power of PV arrays generally deteriorates the quality of power. Monitoring of PV array helps in improving the power quality by changing frequency and voltage of PV array.

Monitoring data of the PV system gives a good insight to the electric power companies in finding avenues to get information about the environmental conditions, to reduce the mal-operation of the system and ways to improve the power quality. When PV power system is connected to the grid, electric power quality becomes the important concern.

5.3.4. Performance evaluation

Performance monitoring is also an important aspect of the PV array monitoring. By monitoring the voltage and output current generated by PV array, the overall annual energy production can be calculated which can be compared with the predicted value. The difference in the energy production determines the performance of the system. Moreover, this data can be used to find the overall cost per watt of production. Power generated can be compared with the environmental data in order to calculate the efficiency of the system.

5.4. DC side monitoring

AC side monitoring doesn’t provide the information about the fault occurring at the module level i.e. fault within the PV array. Monitoring on DC side is required to find the modules which are faulty and many trends in the data collected.

5.4.1. Fault Identification

In order to detect the faults and identifying the modules, the methods dependent upon the human operator, are not reliable. For that reason, automatic fault detection system i.e. monitoring systems are required. They are not only reliable but the more efficient as compare to the manual statistical analysis approach. Such faults at the module level are indistinguishable and the power loss due to these faults, measurement errors cannot be identified easily. And, therefore, there is a need to monitor the system on DC side effectively. In [22], an ad-hoc method is given that gathers the data at the string level and utilizes this data in identifying the fault at string level which reduces the power output by 20% at string level. Moreover, an automated system can be made by using a suitable signal processing algorithm which takes data from each module by using sensor. Here, the accuracy of identifying the ground fault and arc fault is 99% [25]. Such system uses complex algorithm and many sensors which is not feasible in practical systems.

5.4.2. Identifying Trends

Monitoring on DC side can be used to find short/long term patterns. The historical data, let say collected previous year, can be used to compare with this year output data and hence, the performance evaluation of the PV panel can be done. This pattern can be used in finding the factor with which the PV panel performance is degrading. PV output can be compared with different external data sets to optimize the PV models.

5.5. Existing Monitoring Methods

There are many system proposed to monitor at the array and module level. Some methods are suitable for monitoring the effect of external environmental factors on the PV performance while some focus on intra-array monitoring too. Suitability of using a monitoring system depends mainly on the targeted capabilities.

In [29], a system monitor is installed to gather the information of the PV array located at some building terrace. System collects the PV data in terms of voltage, current, power at the output side of the inverter. Temperature is measured by using pyrometer (i.e. temperature sensor) while the irradiance is measured by photo diode sensors. The output of these sensors is averaged at 20 min interval. This data is good for fining both i.e. short term patterns and long term patterns. The short term pattern gives the PV status in current time while the long term tell the degradation in components' performance. Mentoring at string levels gives the comparative view of output power at the partial shadowing case. It tells how much the array is shadowed. The variation of power output with the temperature at constant irradiance is shown to get the effect of the temperature of the solar system performance. Moreover, this data can be used to find overall energy production in a certain period of time and overall cost per watt electricity produced by the array. All the collected data is then transferred to the computer where it gets the internet access. A need of DAQ system is mentioned by the author to transfer data from system to computer.

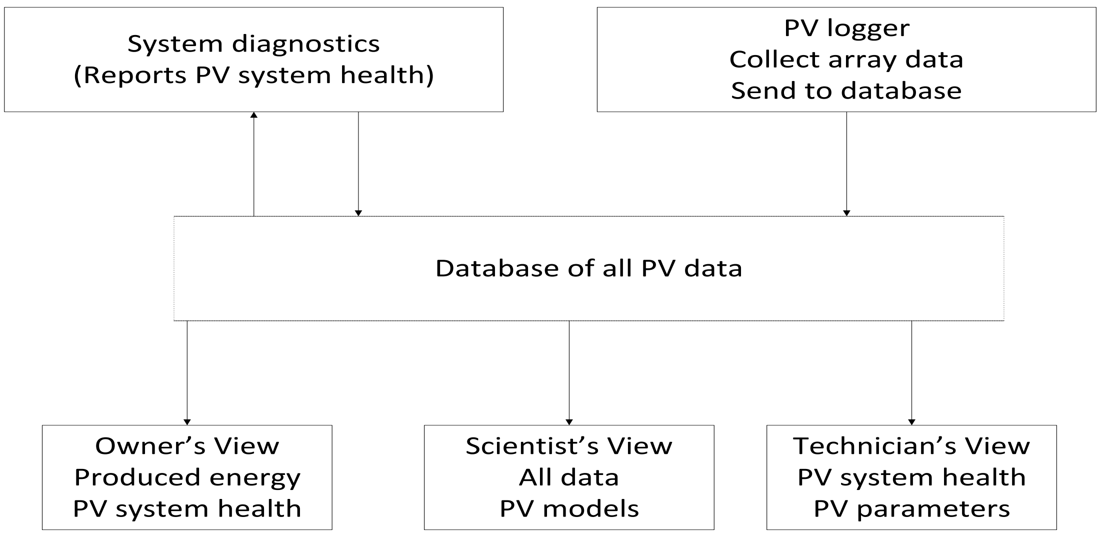


Fig. 5.1 Schematic for fetching the information according to the demand of user

A new methodology of data analysis i.e. XML is used to analyze the collected data in [28]. It is termed as the modern informatics tool. Here, a protocol known as PV mark up language (established by XML) is proposed to fetch and analyze data from different sensors. This system gathers and classify the monitored data and depending upon the user such as technician, scientist or plant owner different patterns after accessing data is presented to give relevant information. The PV logger fetches all the data and keeps updating the database. The system diagnostic then retrieves the information to find out the number of failures and updates the database with new information. It can generate the different information according to the need of the different users. The scientist's view, the owner's view, the technician's view has information such as all the collected data, overall system health and PV system parameters etc. respectively. This method of data analysis provides a very comprehensive approach to store and retrieve data which is used with different weather data and data taken by sensor placed at different location. Therefore, a complete monitoring system not only have data sensing but also user interface and data communication.

One more suitable and cost effective approach is provided in [30], which uses graphical user interface built in LabVIEW. This set-up comprises the number of sensing elements at string level which collects the voltage and current data in online condition and feed to the micro-controller. For sensing the temperature, pyranometer while to transfer data from array to controller, analog multiplexer is used. Moreover, it also includes the sensor for getting irradiance value. The collected data is utilized for both controlling as well as monitoring. Here, microcontroller interfacing is done with laptop where the collected data can be displayed and analyzed by designing GUI in NI LabVIEW. This GUI allows the display of PV actual output, expected value of PV system based on the diode equivalent model as well as battery health. In the above mentioned system, no module level sensing is done.

Many condition monitoring methods based on the statistical and empirical data analysis is mentioned by Sergiu Spataru in [31] which identifies the significant discrepancies in PV output and inverter output measurement but such methods requires a large amount of data sets and knowledge of extensive statistical analysis skills.

5.6. Monitoring System Requirements

In previous section, the different aspect of PV monitoring such as data logging, data management, GUI interface etc. are mentioned. These different aspects as a whole constitute a photo voltaic array monitoring system.

Hence, such a system comprises parameter measurement, sensor placement for gathering data at different points in the system, communication system to transfer the accumulated data, algorithms to managing as well as processing the information and a GUI interface to display the performance of the PV system in different conditions. In this section the different aspects of monitoring are dealt briefly.

5.7. Regression analysis (a new approach for condition monitoring)

This is a new approach of condition monitoring which follows the well-known SAPM (Sandia Array Performance Model) which is used widely in identifying and troubleshooting the problems associated with the PV system. SAPM is based on the database which is empirically collected by extensive testing the modules on the field and, therefore, it is able to predict the PV system output in different environmental conditions with greater accuracy.

Here, the inputs to the condition monitoring system are irradiance, temperature and maximum power Pmp at any point of time of operation. If these inputs are available then there is no need of extensive database as used in SAPM to parametrize the PV system. These inputs are monitored periodically using temperature and irradiance sensor as well as I-V scan of the inverter. Once these inputs are provided, PV system can be parameterized online through regression. There are two phases mentioned as following to implement the condition monitoring….

Learning phase/ commissioning phase

This phase is about parameterizing the PV system based on the inputs provided online. As shown in the figure, inputs are measured through sensor and subjected to regression modelling of parameters. And hence, the online parameters are obtained once the system gets installed. This phase is more about acquiring data in form of the MPP measurements for different sets of irradiance and temperature data. The system has no fault here. This phase can be met with filtering the accumulated data by discarding the low MPP estimates, PV system partial shading as well as faults.

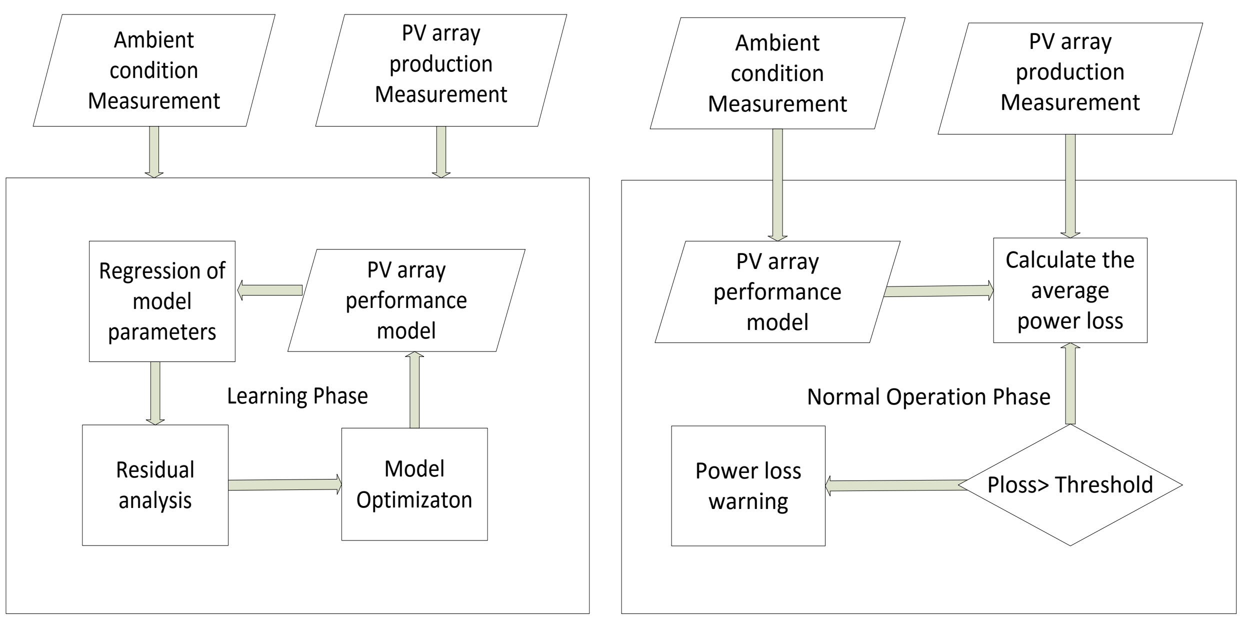


Fig. 5.2 (a) Learning Phase of condition monitoring system, (b) Normal operation phase

Normal operation phase

Once learning phase is over and system is parameterized, the PV system then moves into the normal operation phase where the actual parameters are measured and compared with the expected value of parameters obtained by condition monitoring. The difference between measured an actual gives the value of total P_{loss}. Once this value of P_{loss} is greater than the $P_{threshold}$, the system generates power loss warning.

CHAPTER 6

SIMULATION AND RESULTS

6.1. COMPONENTS

The simulation model broadly consists of 3 main components:

1) Solar panel
2) Buck Boost Converter
3) MPPT (Maximum power point tracking) Algorithm

6.1.1. PV Panel

The PV panel used in this simulation is a User- Defined Block,

Datasheet

Number of Cells per Module = 60

Series Strings = 3

Parallel strings = 1

Maximum Power (W) = 700W

Maximum Power Voltage (Vmpp) = 87.6 V

Maximum Power Current (Impp) = 8.01 A

Open circuit Voltage (Voc) = 111 V

Short Circuit Current (Isc) = 8.54 A

Series resistance of PV module (Ohms) =0.39957

Parallel resistance of PV module (Ohms) = 228.496

Diode saturation current of PV module (A) = 4.11e-10

Light-generated Photo-current of PV module (A) =8.6146

Diode Quality Factor of PV module =1.0108

The PV and IV characteristics of the solar panel used are given in fig. 6.1…

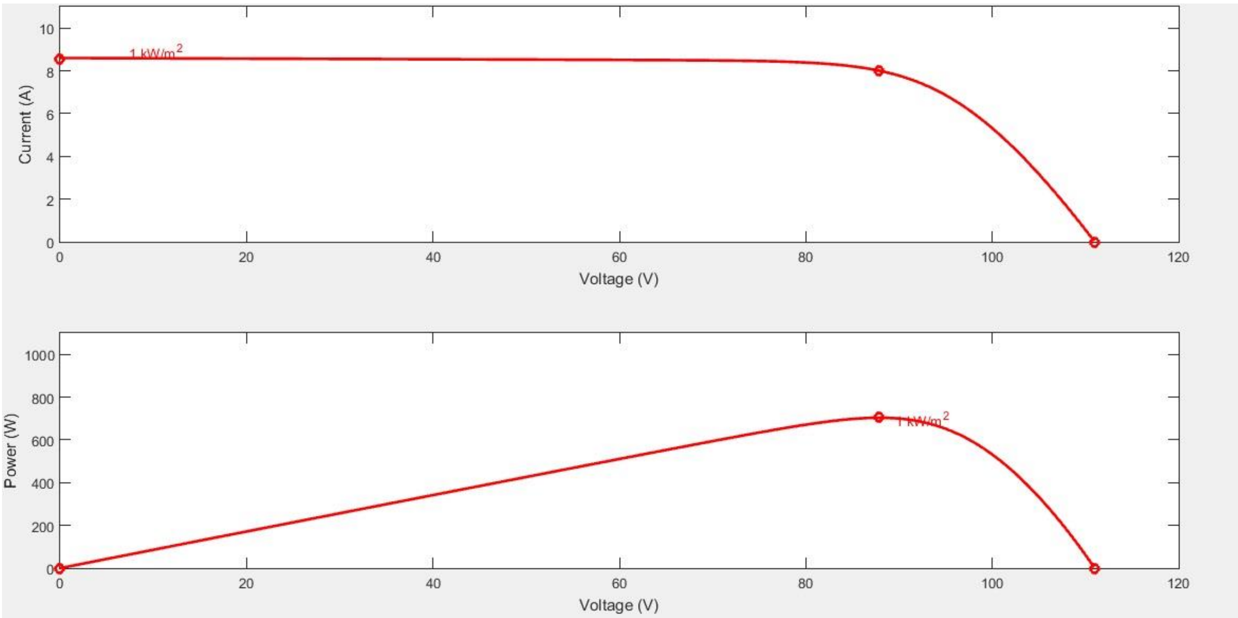


Fig. 6.1: I-V and P-V curve of one Module

6.1.2. Buck Boost Converter Design

A Buck Boost converter is a DC-to-DC power converter with an output voltage greater or less than the input voltage. It does both step-up and step-down of input voltage. The minimum Value of Inductance and Capacitance is calculated by following condition….

As Peak of P-V curve for abovementioned PV array carries 700 W under STC i.e. irradiance 1000 W/m2, temperature 25 °C. So in ideal conditions input power to the Buck-Boost converter will be 700 W and to obtain higher output at converter side, it is needed to operate in step- up mode. V_load is take as 235 Volt and I_load as 3 Amp from power balance equation. Duty cycle can be calculated by,

$$D = \frac{|V_0|}{|V_0|+V_S} = 0\,.73 \text{ (Boost mode of operation)}$$

Critical value of inductor L,

$$L_{min} = \left[\frac{V_S * D}{\Delta i_L * f}\right]$$

For $\Delta i_L = 30\%\ of$ I_L and f_{SW} = 10K, $\boldsymbol{L_{min}}$ **= 21.38mH**

Similarly, Critical value of Capacitor,

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

For voltage ripple 2% of Vo, $\boldsymbol{C_{min} = 49.59e - 6\ Farad}$

6.1.3. Perturb and Observe algorithm

The MATLAB function code and Simulink model for implementing this algorithm are as follows:

```
function D   = P&O (V, I, T)

persistent Pn  Po  dP d dd n;

if isempty (V)
   V=50;
end
if isempty(I)
   I=0;
end
if isempty(Po)
   Po=0;
end
if isempty(Pn)
   Pn=0;
end
if isempty(dP)
   dP=0;
end
if isempty(d)
   d=1;
end
if isempty(dd)
```

```
   dd=0;
end
if isempty(n)
   n=1;
end
if isempty(T)
   T=0;
end

if  (T>n*0.0095)
   Po=Pn;
   Pn=V*I;
   dP=Pn-Po;

   if (dd==0)              % to avoid dP/dd=inf
      if (dP>1)
         dd=0.04;
         d=d+dd;
      else
         if (dP<-1)
            dd=-0.04;
            d=d+dd;
         else
            dd=0;
         end
      end
   else
      if ((dP<1)&&(dP>-1)) % leave little margin
         dd=0;
         d=d+dd;
      else
         if ((dP/dd)>0)  % positive slop
            dd=0.04;
            d=d+dd;
         else            % negative and zero slop
            dd=-0.04;
            d=d+dd;
         end
      end
   end
    n=n+1;
end

D=d/(d+1);  % calculate duty

% code to avoid duty less than 0.1 and more than 0.9
```

```
if (D<0.1)
    D=0.1;
    d=D/ (1-D);
else
    if (D>0.9)
        D=0.9;
        d=D/ (1-D);
    end
end
```

6.1.4. Incremental Conductance based MPPT algorithm

In this simulation, a MATLAB function is created which takes PV panel current and voltage as input calculates instantaneous and incremental conductance. The MATLAB function code for implementing the algorithm is as follows….

```
function D = incCond(Vpv,Ipv,T)  %#codegen

persistent Vprev Iprev n d dd;
if isempty(Vprev)
    Vprev = 0;
end
if isempty(Iprev)
    Iprev = 0;
end
if isempty(n)
    n=1;
end
if isempty(d)
    d=1;
end
if isempty(dd)
    dd=0;
end
if isempty(Vpv)
    Vpv=30;
end
if isempty(Ipv)
    Ipv=2;
end
if  (T>n*0.0095)
deltaI= Ipv-Iprev;
```

```
deltaV = Vpv-Vprev;
 if (deltaV==0)
```

```
        if (deltaI==0)
            dd=0;
            d=d+dd;
        else
            if(deltaI>0)
                dd=.01;
                d=d+dd;
            else
                dd=-.01;
                d=d+dd;
            end
        end
 else
       if((deltaI/deltaV)==(-Ipv/Vpv))
           dd=0;
           d=d+dd;
       else
           if((deltaI/deltaV)>(-Ipv/Vpv))
               dd=.01;
               d=d+dd;
           else
               dd=-.01;
               d=d+dd;
           end
       end
 end
        Vprev = Vpv;
        Iprev = Ipv;
        n=n+1;
 end
 D=d/(d+1); % code to avoid duty less than 0.1 and more than 0.9
if (D<0.1)
    D=0.1;
    d=D/(1-D);
else
    if (D>0.9)
        D=0.9;
        d=D/(1-D);
    end
end
```

Simulink Model

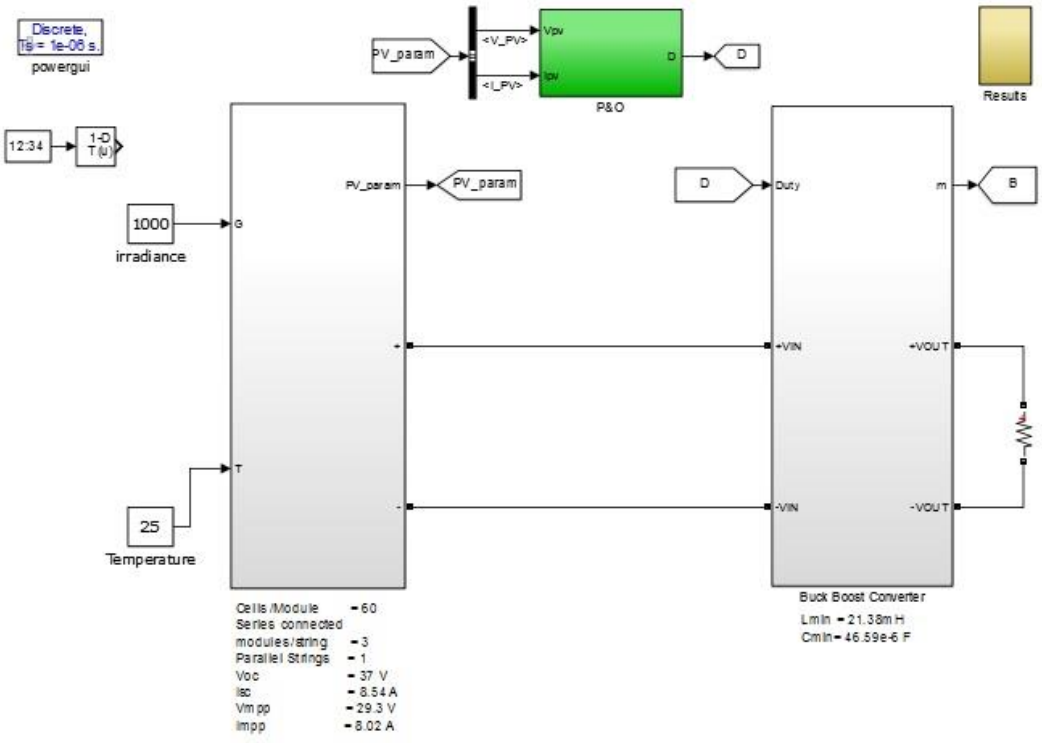


Fig 6.2: Simulink Model of PV system connected with converter and MPPT

6.2. Simulation Results

6.2.1. Standard Test Condition (1000 W/m2 , 25° C)

Without MPPT

In first case model is simulated without MPPT control. This means MPPT control subsystem will turned off and a constant signal of 60% duty cycle is fed into the switch. The complete output is shown in the figure 6.3, 6.4. Important point here to notice is that power output of PV panel without MPPT is 600 W under STC.

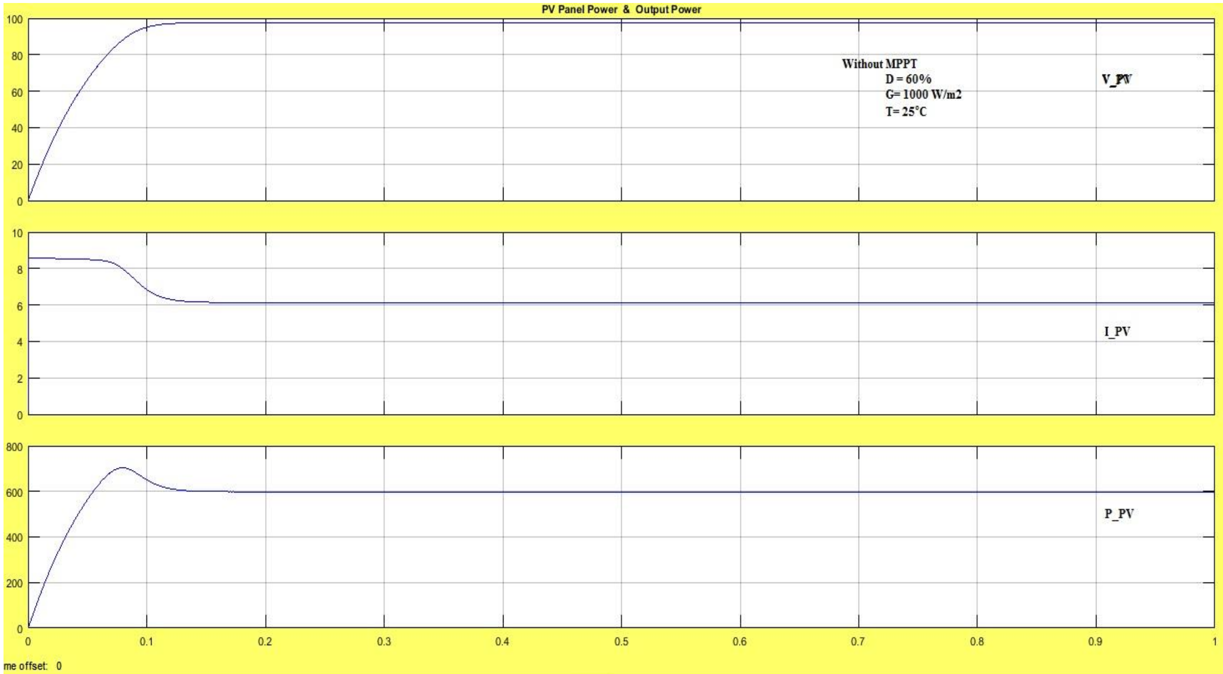


Fig. 6.3(a): PV voltage, current and Power without MPPT

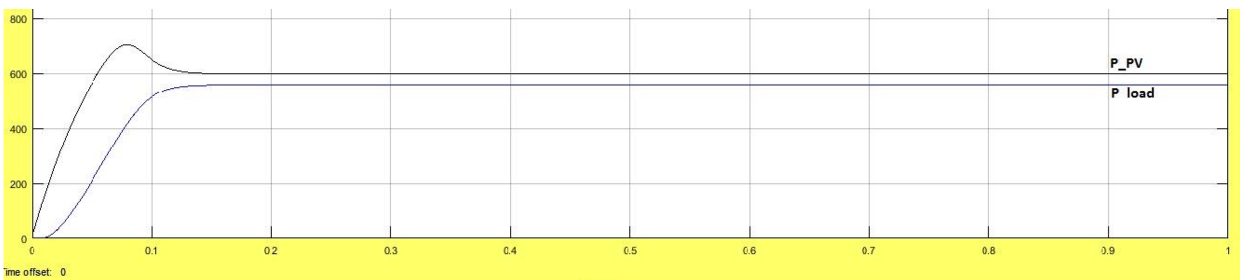


Fig. 6.3(b): Comparison of power without MPPT

With MPPT

Here maximum extract of PV power output is 700 W which is Peak power point under STC. Output voltage is 87.9 Volt that is Vmpp and output current is 8.01 A that is Impp.

It should be noted that at irradiance 1000 W/m2, approx. 700 W is being fed to resistor. From fig. 6.5, the output of the PV panel is within the safe range.

Fig. 6.4(a): PV voltage, current and Power with MPPT

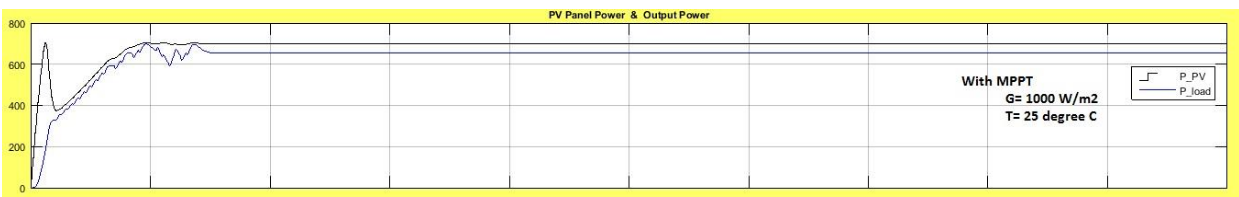


Fig. 6.4(b): Comparison of power with MPPT

5.2.1. Variation in Irradiance

Irradiance is varied as 1000 to 500 to 800 W/m2 at 0.5 sec of interval. We can see here in both the cases, the output is in safe limit and with MPPT , the system is working at its peak point.

Without MPPT

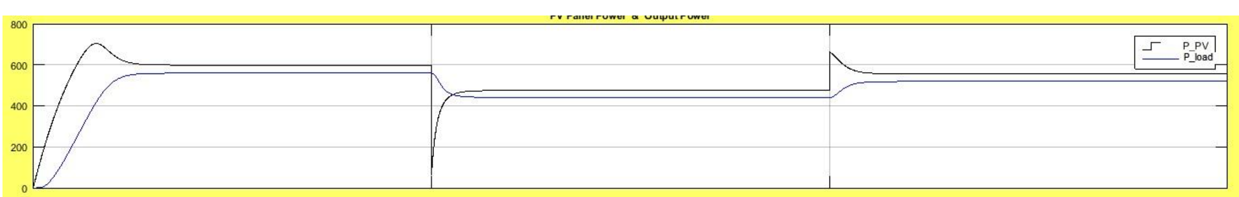


Fig. 6.5(a): Comparison of power without MPPT

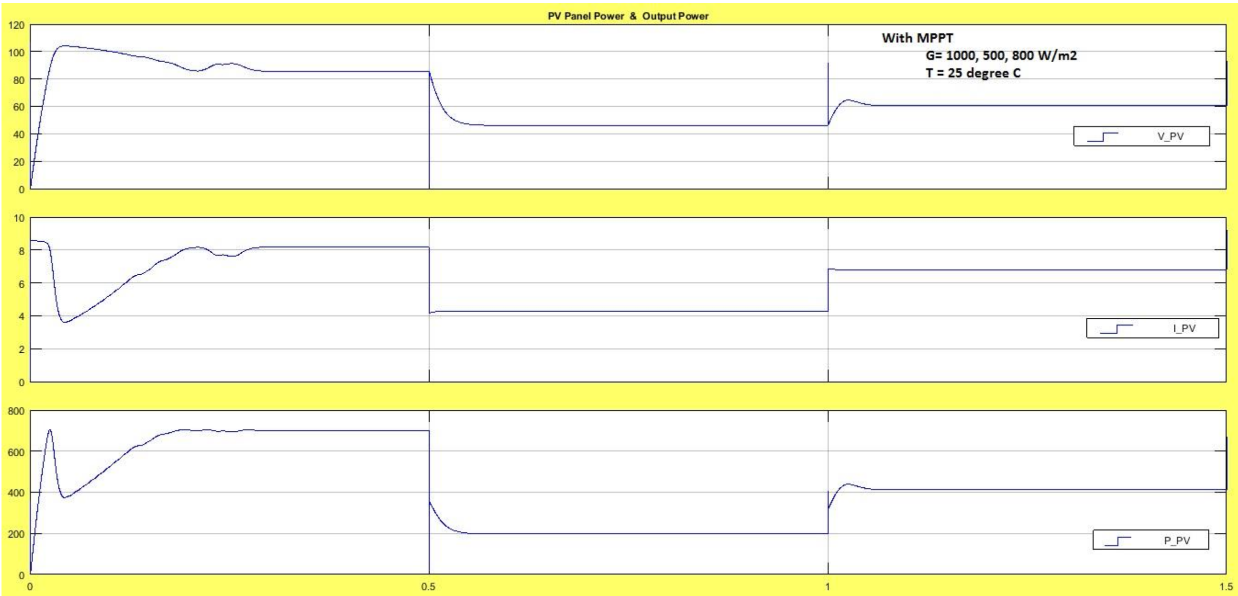


Fig. 6.5(b): PV voltage, current and power without MPPT

With MPPT

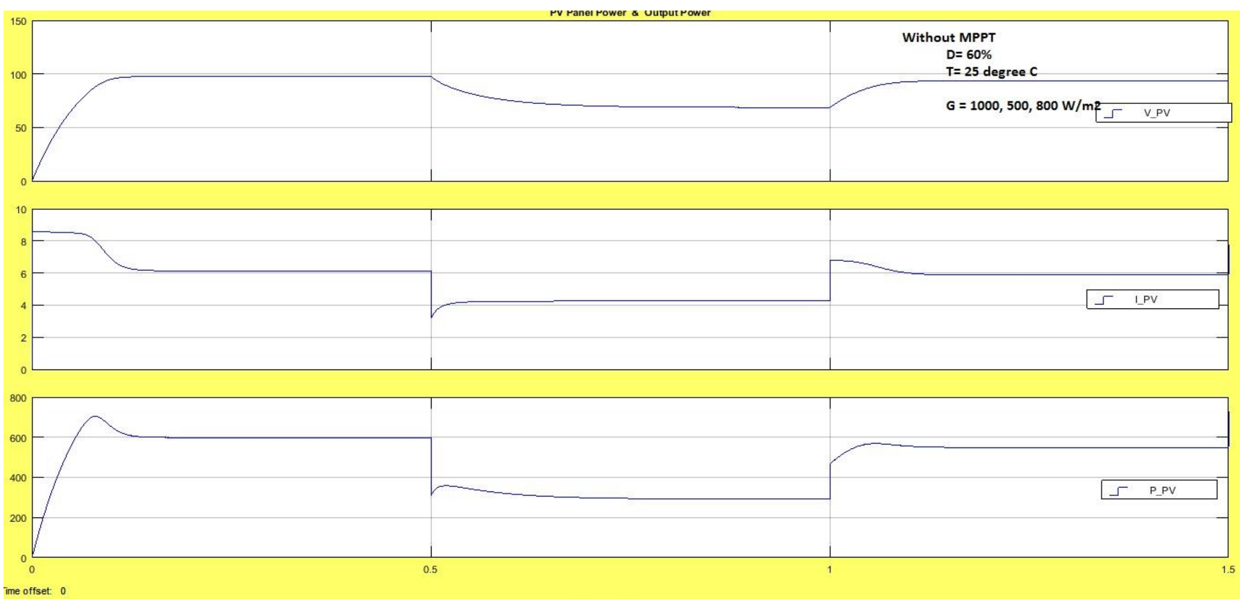


Fig. 6.6(a): PV voltage, current and power with MPPT

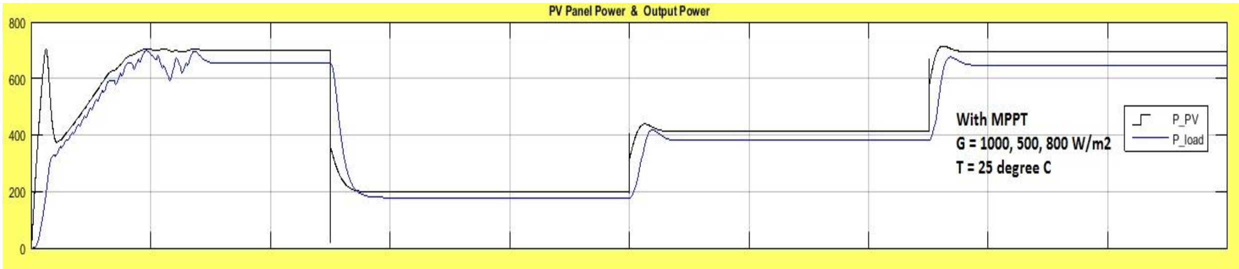


Fig. 6.6(b): Comparison of power with MPPT

5.2.2. Variation in Temperature

Here temperature is changed from 25 degree to 55 degree to 35 degree Celsius. Here also, in both the case, PV output is with in safe limit. And with MPPT, PV panel is working at its maximum efficiency.

Without MPPT

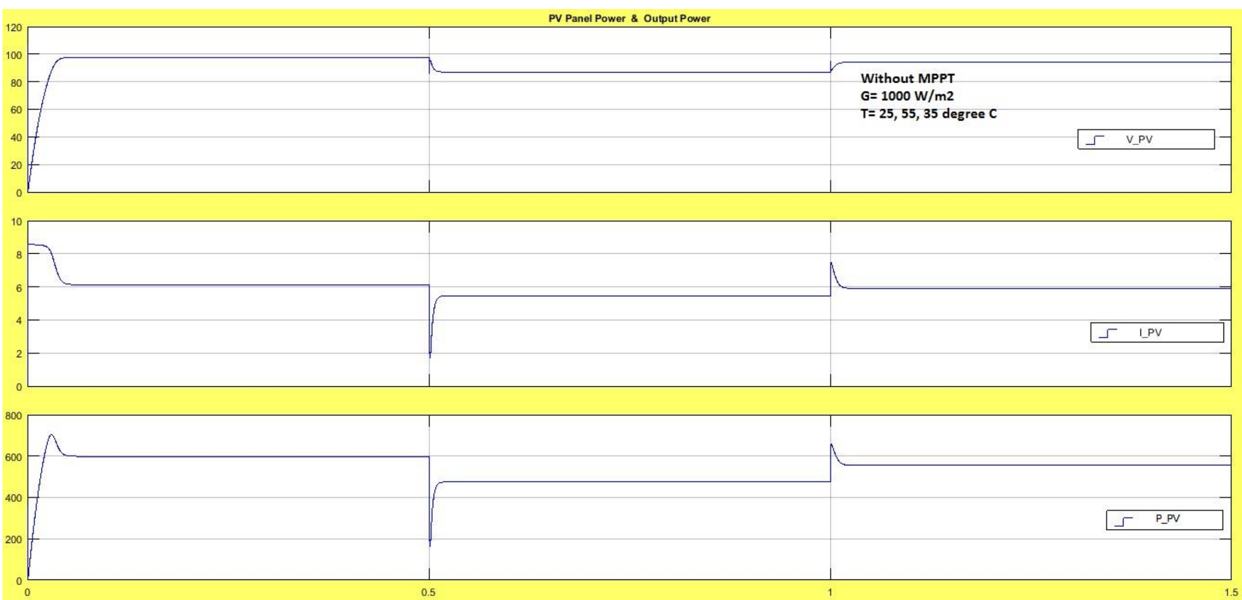


Fig. 6.7(a): PV voltage, current and power without MPPT

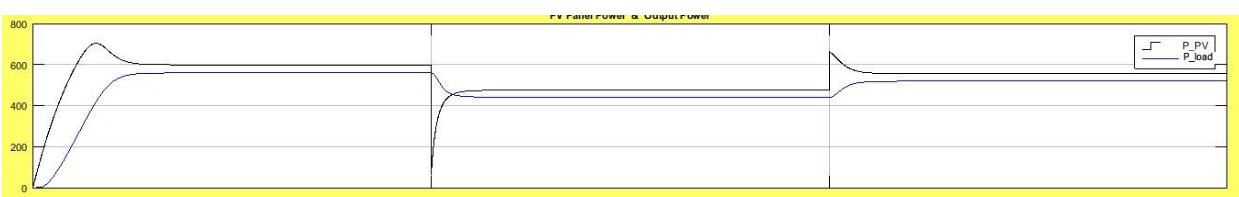


Fig. 6.7(b): Comparison of power without MPPT

With MPPT

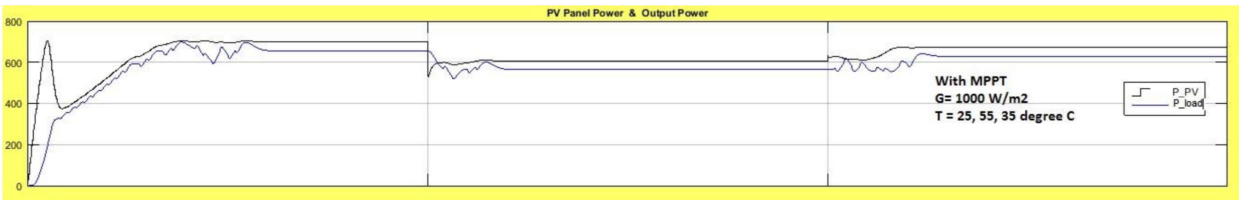


Fig. 6.8(a): Comparison of power with MPPT

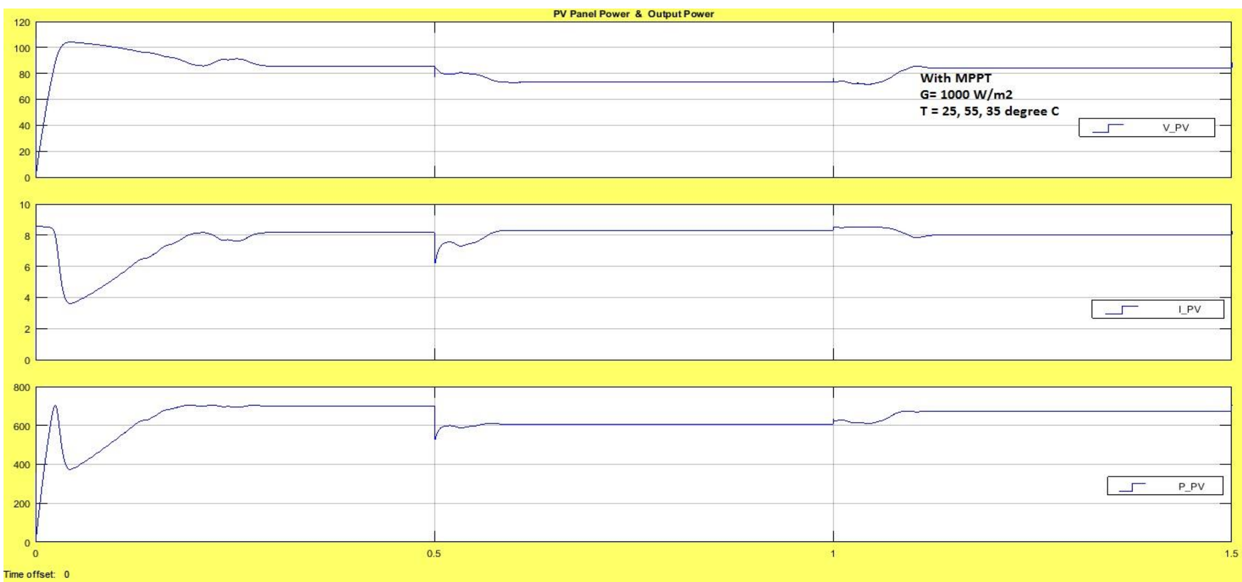


Fig. 6.8(b): PV voltage, current and power with MPPT

6.2.3. Partial Shading

Simulink model

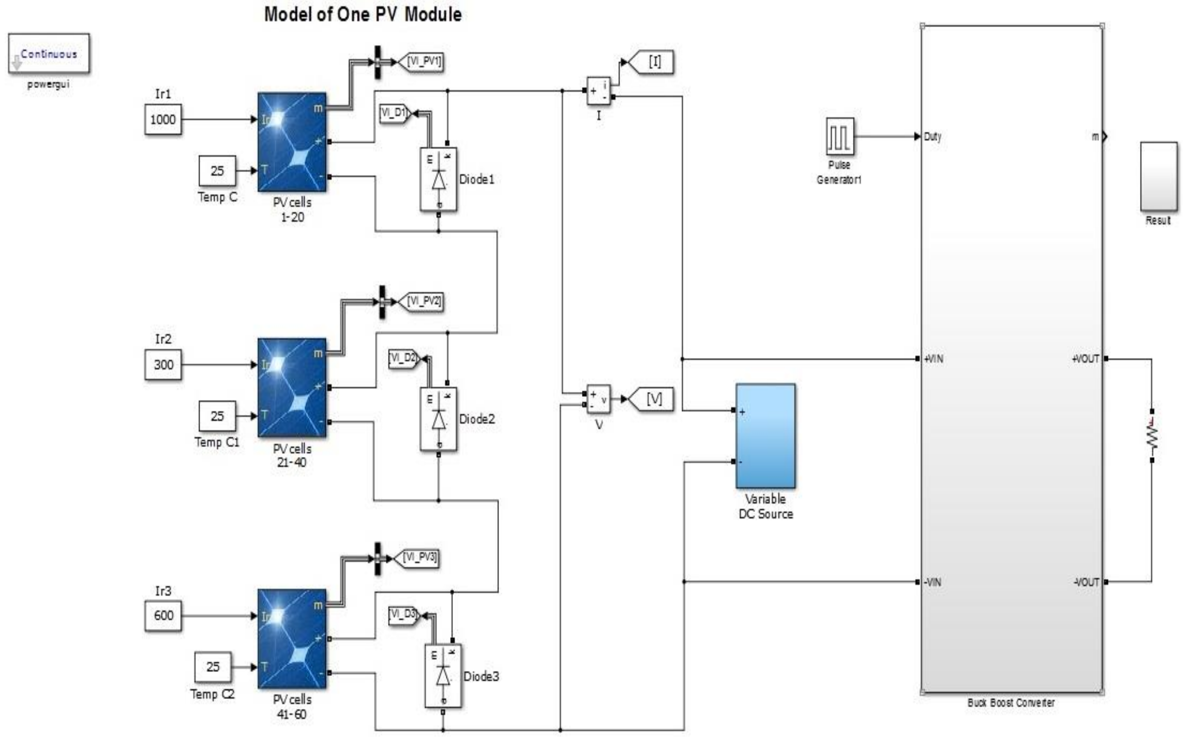


Fig. 6.9: Simulink model of PV system under partial condition

P-V and I-V curve for Partial Shading

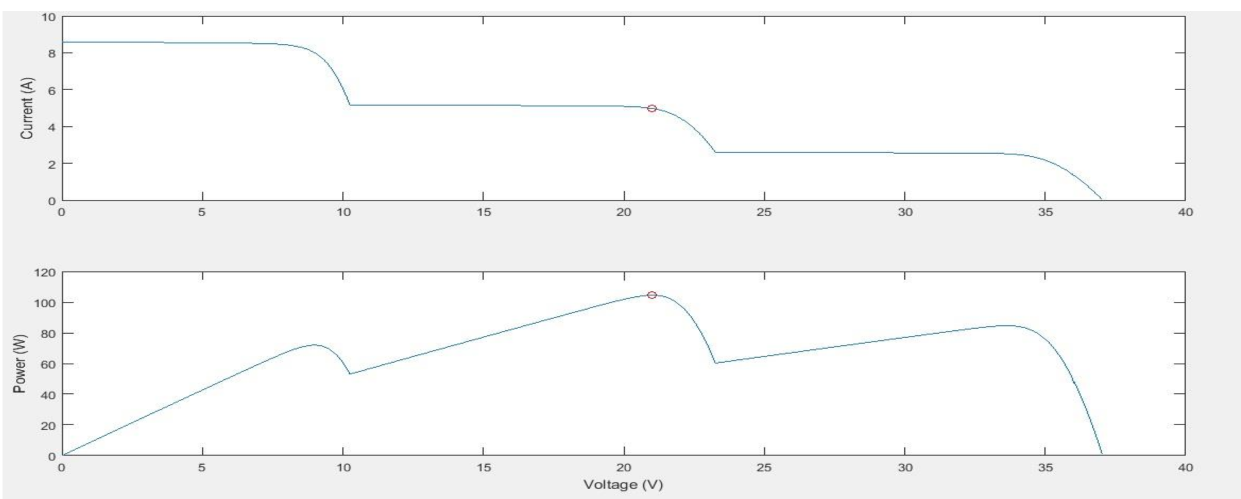


Fig.6.10: P-V and I-V curve for Partial Shading

6.3. Condition monitoring (Data Collection and Data Analysis)

The three main aspects of the monitoring system are….

- Data collection at different level (such as array level, string level etc.)
- Data analysis to deliver meaning information from collected data. This is the most crucial part of monitoring.
- Dissemination of information obtained from data analysis.

6.3.1. Data collection

The monitoring system should be able to measure the following parameters at any point of time when the system is supplying power….

- Irradiance
- Ambient temperature
- Cell temperature
- Output voltage
- Output current
- Maximum power
- Open circuit voltage (Voc)
- Short circuit current (Isc)

In order to obtain condition monitoring, there should be an estimated set of data which is constantly compared with actual data in running condition. This comparison provides the information about the health of the system as well as performance evaluation in long term. Among all parameters, maximum power point is very crucial as well as most difficult to estimate. Therefore, a new method of regression analysis is used to find out the estimated value of maximum power. This estimation of data is termed as learning phase of the system. Once this estimation is done, the system goes into Normal operation phase where the system is run in actual condition. And the result of normal operation phase is compared with the estimated one.

A generic model which is adopted from the Sandia Array Performance Model (SAPM), proposes the seven variables which are trained to adapt the nonlinearity of the model. These variables are called regressors [14].

$$X_1 = T_c * \ln(G), X_2 = (T_c * \ln(G))^2$$

$$X_3 = \Delta T, X_4 = G, X_5 = G^2 \quad (6.1)$$

$$X_6 = G * \Delta T, X_7 = G^2 * \Delta T$$

A multiple linear regression model is formulated based on these variables. The regression coefficients p_i need to be calculated for estimating the maximum power by using the following equation…

$$Pmp(G, Tc) = \sum pi * xi + \epsilon \ \ where\ xo = 1 \quad (6.2)$$

By using equation (1), (2), the regression coefficients are calculated with help of least square method. And the training data is generated for the learning phase of the system. This is how the maximum power point can be estimated by this model. For the validation of the data estimated, some indicators like root mean square error (RMSE), Coeff. Of determination R^2 is observed.

6.3.2. Data Analysis

The data is categorized for following cases…

Case 1 : Irradiance is varying while temperature is 25 degree Celsius.

Regression Summary

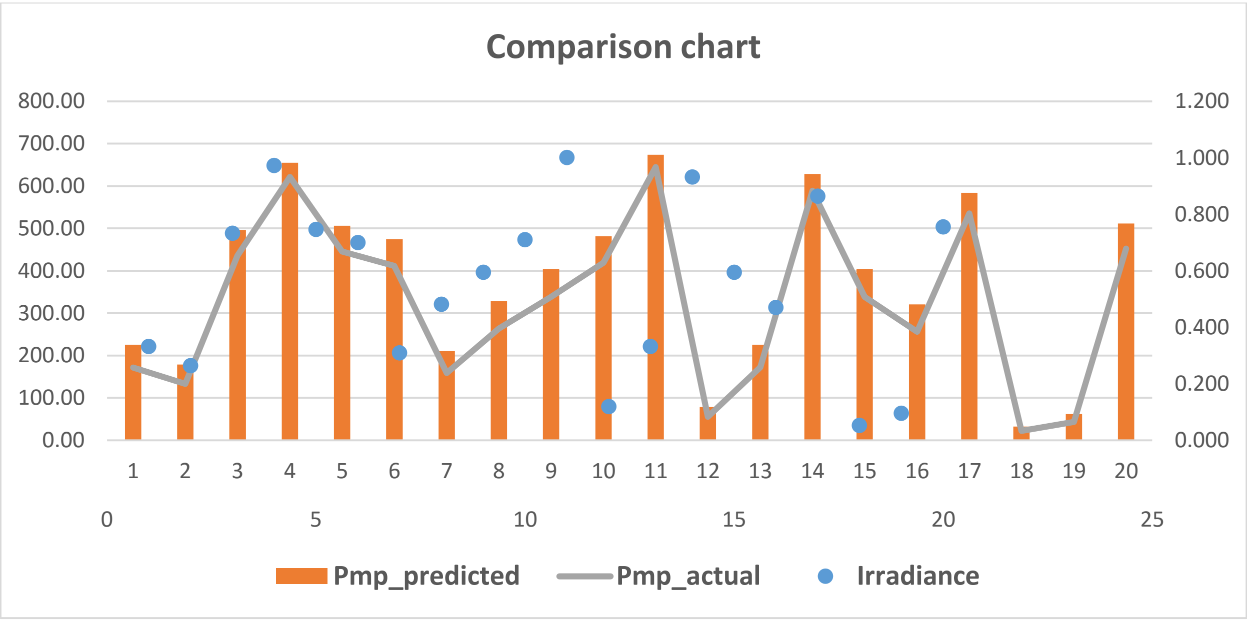
Regres+A3:G23sion Statistics	
Multiple R	0.9509371
R Square	**89%**
Adjusted R Square	0.80571233
Standard Error	9.5183719
Observations	20

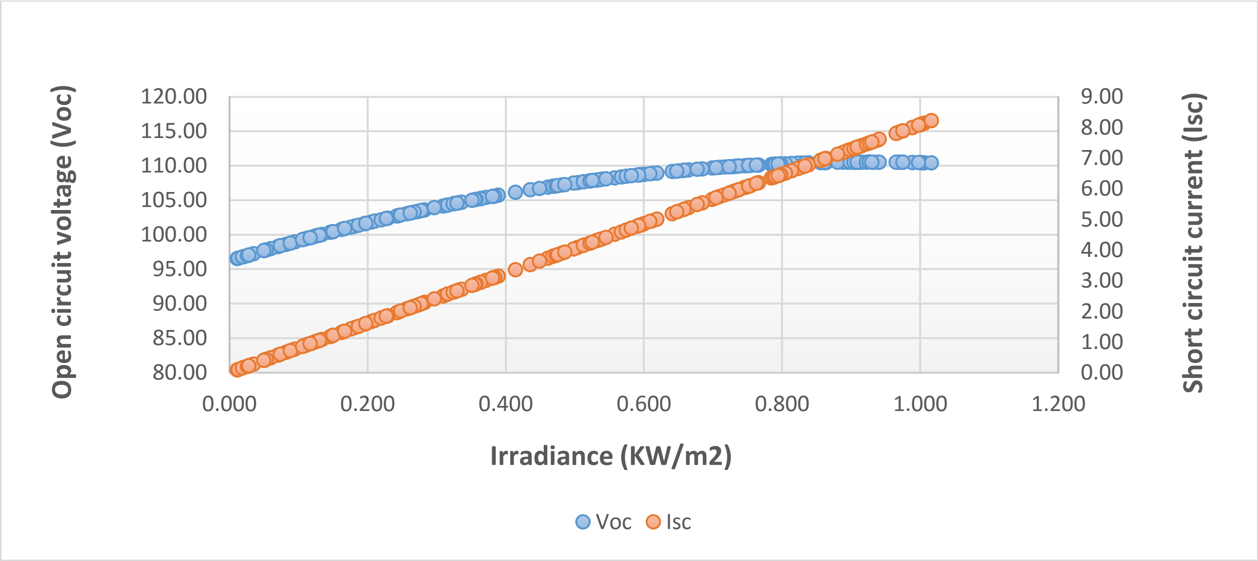
ANOVA

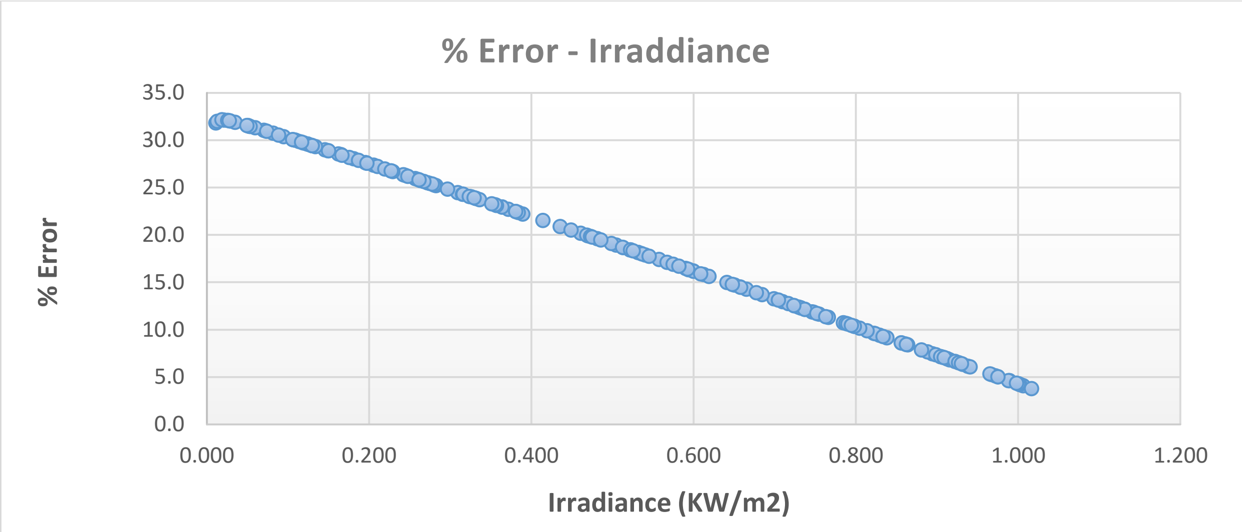
	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	62274.0325	311308.7519	9.2E+02	0.00000008
Residual	9	63513	927419.31		
Total	15	125787.0325			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**138**	2.91E-02	0.254619	0.00926433	12.71936	121.24671
x1	**0.000630**	2.56E+02	0.04946206	-66.342561	1.09465	52.76209
x2	**-0.008129**	5.66E+03	-0.6396281	3.92134	9.283645	14.93209
x3	**0**	0	0	0	0	0
x4	**23.74091**	9.627E-02	11.002901	1.46E-02	0.0234588	-0.65218938
x5	**11.47820**	5.309E-01	-1.547782	-0.0035729	0.9662	2.38E-02
x6	**0.518344**	1.347E+01	9.19340	0.0418258	-294.823	457.556

The above mentioned summary gives the coefficients of the equation used for regression. By using these coefficients, predicted values of maximum power are obtained.







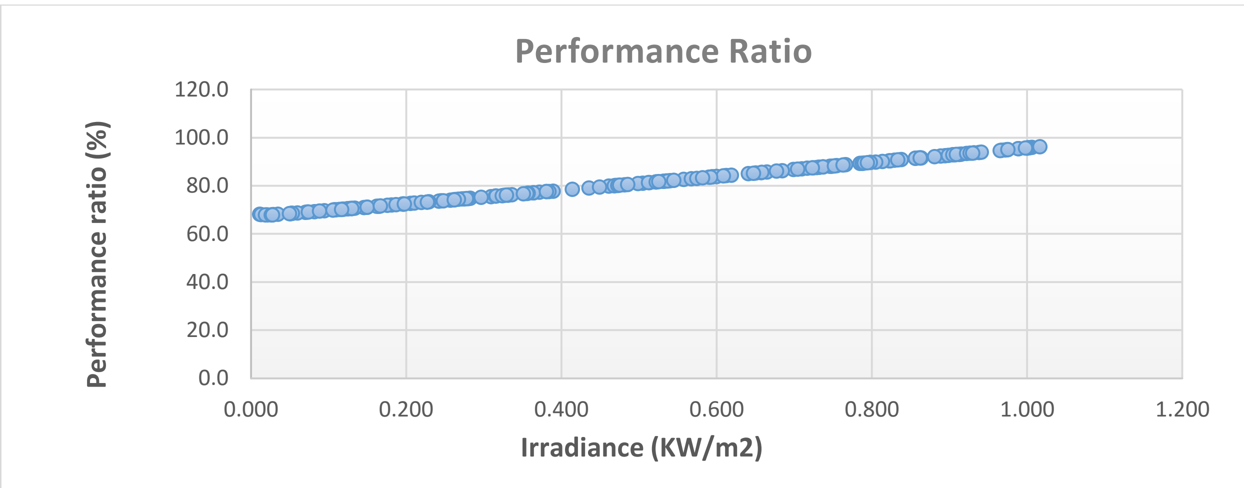


Fig 6.11.(a) Measured Vs. Actual Maximum power, (b) Voc and Isc variation with irradiance (c) Percentage error Vs. Irradiance, (d) Performance ratio Vs. Irradiance

Case 2: Temperature is varying while Irradiance is 1 KW/m^2

Regression Summary

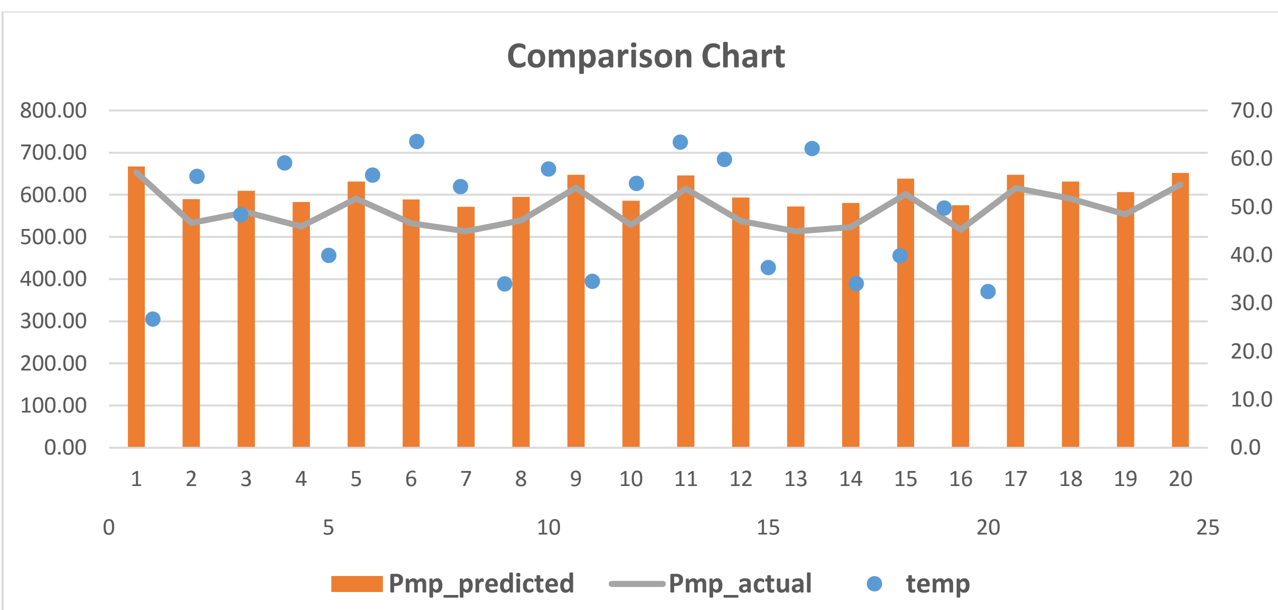
Regres+A3:G23sion Statistics	
Multiple R	0.9189112
R Square	**84%**
Adjusted R Square	0.80571233
Standard Error	27.174116

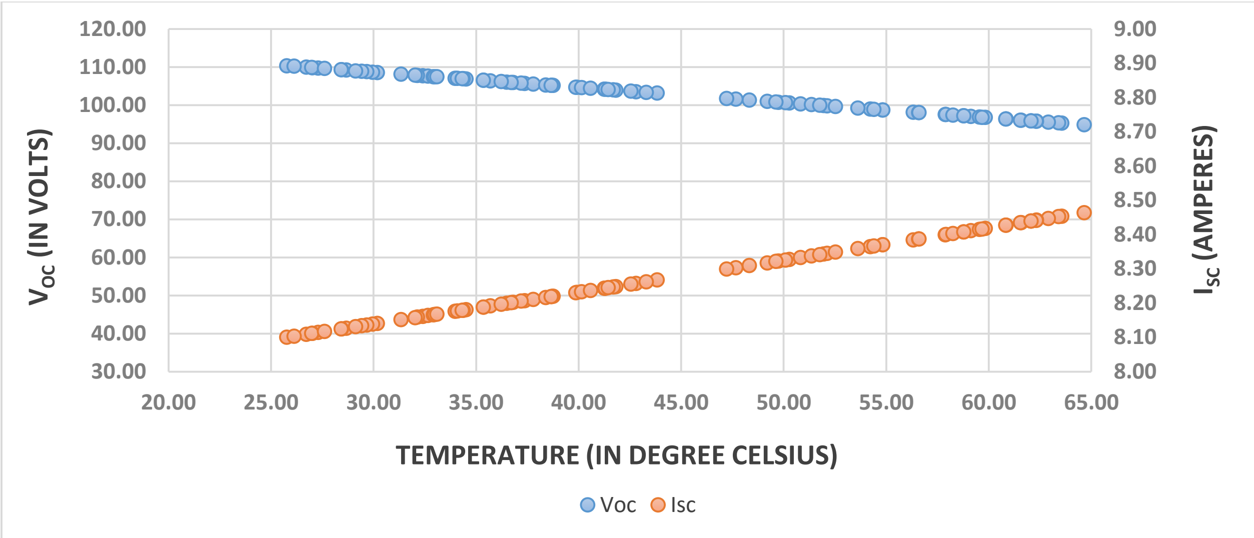
Observations	16

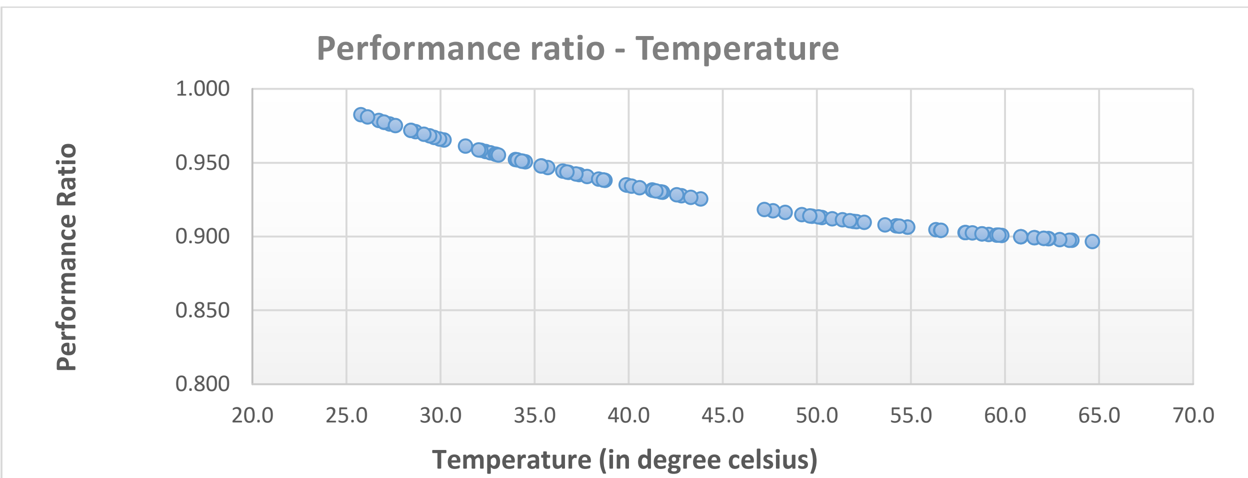
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	896234.4805	149372.413	2.92E+01	0.0000058
Residual	9	5106772	567419.11		
Total	15	1463653.611			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**65**	4.10E-01	-0.4270343	6.7939E-05	4.41E+02	642.87264
x1	**-2.31114**	3.32E-02	0.04946206	0.00096163	47.094735	62.786235
x2	**-5.894562**	4.56E-01	-0.6396281	0.00538353	13.452272	15.06329
x3	**-0.0875432**	1.27E+01	2.55907143	0.80377556	- 2.54881997	- 3.199049228
x4	**3.76843**	6.36E-01	11.002901	1.46E-02	0.0234588	-0.65218938
x5	**7.673298**	2.11E+02	-113.57005	0.16854195	-7.0562	2.38E-02
x6	**11.65423**	2.03E+03	-42.778	0.61418258	-186.8	78.999







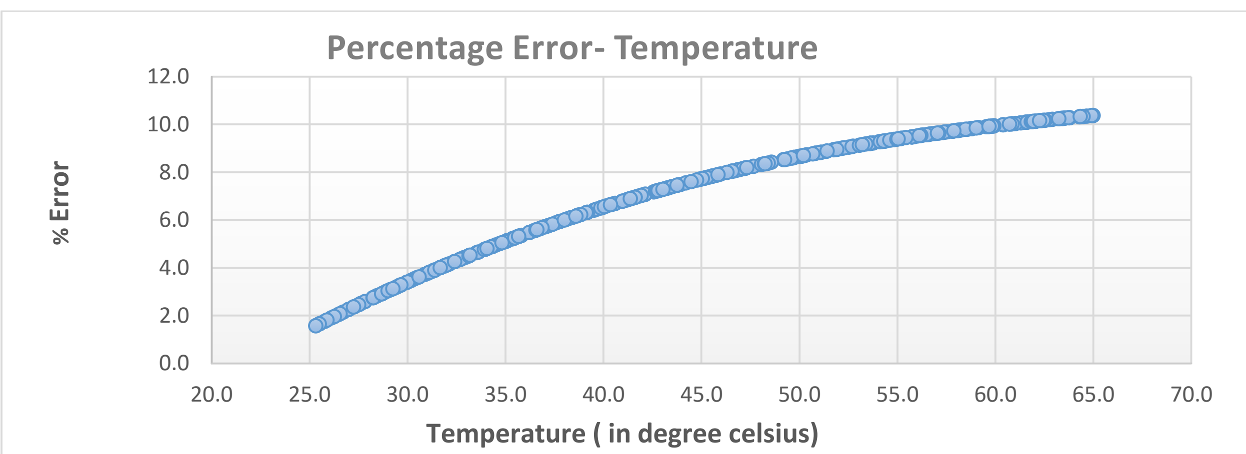


Fig 6.12.(a) Measured Vs. Actual Maximum power, (b) Voc and Isc variation with Temperature (c) Performance ratio Vs. Temperature, (d) Percentage error Vs. Temperature

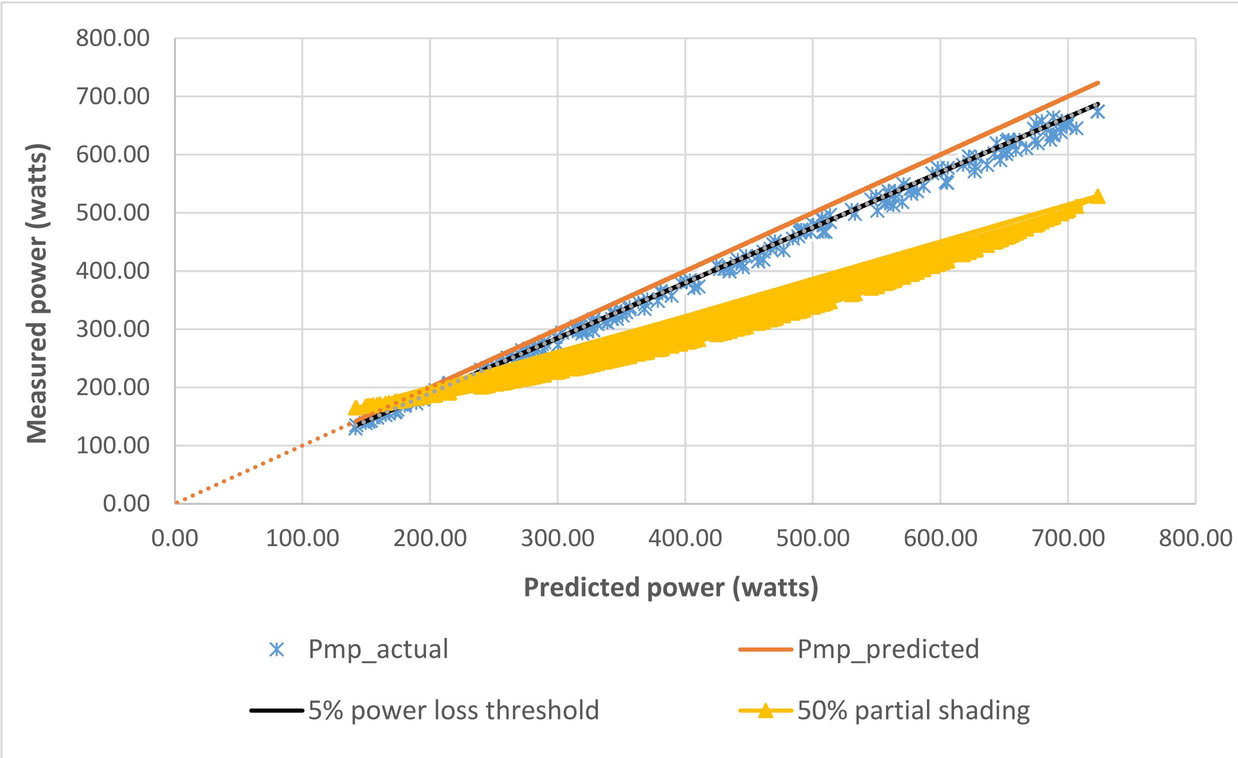


Fig. 6.13. Variation of measured power with partial shading

CONCLUSION

This dissertation gives the brief overview over the necessity of the renewable energy source i.e. solar power system and the need of constantly monitoring the solar panel with the requirement of necessary technology which is easily accessible to all. Moreover, a detailed overview of the solar cell and its characteristic is also provided. The factors affecting the solar module are explained. In different meteorological conditions, the maximum power point of the system changes and many times, MPPT fails to track the maximum power. Moreover, in many other faulty conditions, the system doesn’t behave well. The Monitoring of PV system has addressed these issues in this work successfully.

This report explains that the most solar system are designed for ideal conditions but with the change in external conditions, performance of solar panel is affected. The effects of external conditions are monitored through data collection and data analysis. The results of data analysis are shown in graphs and charts. This data not only helps in condition monitoring of the system at any given point of time but also provides information how to get maximum energy yield, design flaws, reliability of system etc. The most difficult part of condition monitoring of any system is to predict the maximum power in different environmental conditions. In this work, a new method of regression analysis, curve fitting is used to predict the maximum power value at different conditions. And these predicted parameters are compared with the actual one to ensure the health of the system. Hence, condition monitoring of PV system is an important aspect which not only gives the short term trends and patterns but also improves the efficiency and life of the system.

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APPENDIX A

Table of PV parameters estimated and measured

Case1: Varying temperature

Temp	Vmp_pre	Vmp_act	Imp_pre	Imp_act	Voc	Isc	Pmp_actual	Pmp_predict	% error
32.9	85.86	84.40	7.61	7.36	107.53	8.17	621.59	650.41	4.43
63.4	73.87	70.50	7.75	7.28	95.35	8.45	513.49	572.15	10.25
64.3	73.50	69.95	7.75	7.31	94.97	8.46	510.98	569.84	10.33
49.7	79.25	77.65	7.69	7.13	100.82	8.32	553.98	606.22	8.62
33.5	85.62	84.20	7.62	7.35	107.29	8.17	618.75	648.79	4.63
44.1	81.48	80.18	7.66	7.16	103.08	8.27	574.13	620.82	7.52
63.5	73.81	70.41	7.75	7.29	95.29	8.45	513.09	571.78	10.26
47.8	80.01	78.54	7.68	7.14	101.59	8.30	560.58	611.17	8.28
26.8	88.26	86.29	7.59	7.56	109.97	8.11	652.48	667.07	2.19
29.6	87.15	85.46	7.60	7.46	108.85	8.14	637.80	659.36	3.27
56.6	76.53	74.22	7.72	7.17	98.05	8.39	532.30	588.77	9.59
33.0	85.81	84.36	7.62	7.36	107.48	8.17	620.96	650.06	4.48
59.6	75.37	72.64	7.73	7.21	96.87	8.42	523.84	581.45	9.91
33.7	85.53	84.12	7.62	7.34	107.20	8.17	617.65	648.16	4.71
46.0	80.72	79.35	7.67	7.15	102.31	8.29	566.98	615.80	7.93
28.9	87.43	85.67	7.60	7.49	109.13	8.13	641.43	661.30	3.00
63.8	73.71	70.26	7.75	7.29	95.19	8.46	512.38	571.13	10.29
54.6	77.32	75.25	7.71	7.15	98.85	8.37	538.28	593.77	9.35
32.2	86.14	84.64	7.61	7.38	107.82	8.16	625.07	652.38	4.19
28.0	87.80	85.95	7.59	7.52	109.50	8.12	646.27	663.85	2.65
36.7	84.38	83.09	7.63	7.27	106.03	8.20	604.36	640.32	5.62
40.3	82.97	81.72	7.65	7.21	104.59	8.23	589.02	630.75	6.62
29.3	87.26	85.54	7.60	7.47	108.95	8.13	639.19	660.11	3.17
62.9	74.07	70.78	7.74	7.27	95.55	8.45	514.80	573.34	10.21
26.9	88.21	86.26	7.59	7.56	109.92	8.11	651.83	666.74	2.24
51.4	78.57	76.83	7.69	7.14	100.12	8.34	548.26	601.79	8.90
63.5	73.82	70.42	7.75	7.29	95.30	8.45	513.14	571.82	10.26
33.9	85.48	84.08	7.62	7.34	107.15	8.17	617.07	647.83	4.75
27.3	88.08	86.16	7.59	7.54	109.79	8.11	650.08	665.83	2.37
29.7	87.14	85.44	7.60	7.46	108.83	8.14	637.59	659.25	3.28
61.9	74.44	71.33	7.74	7.25	95.93	8.44	517.37	575.67	10.13
32.6	85.98	84.50	7.61	7.37	107.65	8.16	623.00	651.21	4.33
46.2	80.64	79.26	7.67	7.14	102.23	8.29	566.29	615.31	7.97
50.5	78.96	77.30	7.69	7.13	100.52	8.33	551.50	604.32	8.74
58.1	75.96	73.45	7.72	7.19	97.47	8.40	528.08	585.15	9.75
37.3	84.11	82.84	7.63	7.26	105.76	8.21	601.33	638.48	5.82
32.9	85.86	84.40	7.61	7.36	107.53	8.17	621.60	650.42	4.43

29.8	87.07	85.39	7.60	7.46	108.76	8.14	636.76	658.80	3.35
58.0	75.98	73.49	7.72	7.19	97.50	8.40	528.27	585.32	9.75
44.5	81.32	80.01	7.66	7.16	102.91	8.27	572.59	619.76	7.61
33.6	85.58	84.16	7.62	7.35	107.25	8.17	618.26	648.51	4.66
49.9	79.18	77.57	7.69	7.13	100.75	8.32	553.40	605.78	8.65
35.9	84.67	83.36	7.63	7.29	106.33	8.19	607.64	642.29	5.40
29.4	87.22	85.51	7.60	7.47	108.92	8.13	638.71	659.84	3.20
46.6	80.46	79.06	7.67	7.14	102.05	8.29	564.63	614.12	8.06
51.4	78.58	76.84	7.69	7.14	100.13	8.34	548.36	601.88	8.89
57.2	76.31	73.93	7.72	7.18	97.83	8.39	530.66	587.37	9.65
39.4	83.31	82.07	7.64	7.22	104.95	8.23	592.69	633.09	6.38
40.6	82.83	81.58	7.65	7.20	104.45	8.24	587.57	629.81	6.71
64.5	73.43	69.84	7.75	7.31	94.90	8.46	510.51	569.41	10.34
32.9	85.88	84.42	7.61	7.37	107.55	8.17	621.86	650.57	4.41
34.7	85.17	83.80	7.62	7.32	106.83	8.18	613.33	645.66	5.01
35.8	84.72	83.40	7.63	7.29	106.37	8.19	608.15	642.60	5.36
39.6	83.23	81.99	7.64	7.22	104.86	8.23	591.78	632.51	6.44
51.4	78.59	76.85	7.69	7.14	100.14	8.34	548.42	601.93	8.89
50.4	78.96	77.31	7.69	7.13	100.52	8.33	551.53	604.34	8.74
55.3	77.04	74.89	7.71	7.16	98.57	8.38	536.14	592.00	9.44
46.8	80.41	79.00	7.67	7.14	102.00	8.29	564.20	613.81	8.08
51.4	78.58	76.84	7.69	7.14	100.13	8.34	548.34	601.86	8.89
59.1	75.55	72.90	7.73	7.20	97.06	8.41	525.16	582.61	9.86
63.3	73.93	70.58	7.75	7.28	95.41	8.45	513.84	572.46	10.24
27.1	88.15	86.21	7.59	7.55	109.86	8.11	651.04	666.33	2.29
52.0	78.33	76.54	7.70	7.14	99.88	8.34	546.34	600.28	8.99
61.3	74.70	71.69	7.74	7.24	96.19	8.43	519.12	577.25	10.07
61.5	74.61	71.56	7.74	7.25	96.10	8.43	518.50	576.69	10.09
29.4	87.23	85.51	7.60	7.47	108.92	8.13	638.74	659.86	3.20
39.5	83.26	82.02	7.64	7.22	104.89	8.23	592.11	632.72	6.42
51.6	78.49	76.73	7.70	7.14	100.04	8.34	547.62	601.29	8.93
31.0	86.60	85.01	7.61	7.42	108.28	8.15	630.69	655.49	3.78
27.1	88.13	86.20	7.59	7.55	109.84	8.11	650.81	666.21	2.31
33.7	85.56	84.14	7.62	7.34	107.22	8.17	617.94	648.33	4.69
58.0	75.99	73.50	7.72	7.19	97.51	8.40	528.34	585.38	9.74
41.4	82.50	81.26	7.65	7.19	104.12	8.25	584.29	627.66	6.91
55.8	76.87	74.67	7.71	7.16	98.40	8.38	534.85	590.92	9.49
46.4	80.55	79.16	7.67	7.14	102.14	8.29	565.44	614.70	8.01
47.0	80.32	78.90	7.68	7.14	101.91	8.30	563.41	613.23	8.12
47.7	80.03	78.57	7.68	7.14	101.61	8.30	560.76	611.29	8.27
33.5	85.62	84.20	7.62	7.35	107.29	8.17	618.70	648.77	4.63
35.5	84.85	83.52	7.63	7.30	106.51	8.19	609.67	643.50	5.26
32.7	85.92	84.46	7.61	7.37	107.60	8.16	622.38	650.86	4.38

47.0	80.32	78.90	7.68	7.14	101.91	8.30	563.39	613.22	8.13
43.7	81.61	80.32	7.66	7.16	103.21	8.27	575.43	621.71	7.44
47.4	80.14	78.70	7.68	7.14	101.72	8.30	561.77	612.04	8.21
56.2	76.69	74.43	7.72	7.17	98.21	8.38	533.49	589.78	9.54
36.7	84.37	83.08	7.63	7.27	106.02	8.20	604.20	640.23	5.63
44.4	81.35	80.04	7.66	7.16	102.95	8.27	572.91	619.98	7.59
50.1	79.11	77.48	7.69	7.13	100.67	8.33	552.77	605.30	8.68
55.5	76.97	74.80	7.71	7.16	98.50	8.38	535.63	591.57	9.46
34.9	85.06	83.70	7.62	7.31	106.72	8.18	612.06	644.92	5.09
55.5	76.98	74.82	7.71	7.16	98.51	8.38	535.69	591.62	9.45
61.0	74.80	71.84	7.74	7.24	96.30	8.43	519.87	577.92	10.04
39.5	83.27	82.03	7.64	7.22	104.90	8.23	592.26	632.82	6.41
45.6	80.87	79.52	7.67	7.15	102.46	8.28	568.41	616.82	7.85
46.9	80.34	78.92	7.68	7.14	101.93	8.30	563.57	613.35	8.12
34.6	85.19	83.82	7.62	7.32	106.85	8.18	613.62	645.83	4.99
60.9	74.86	71.92	7.74	7.23	96.36	8.43	520.26	578.27	10.03
35.6	84.80	83.47	7.63	7.30	106.46	8.19	609.12	643.18	5.29
60.5	75.02	72.15	7.73	7.23	96.51	8.42	521.36	579.25	9.99
45.0	81.09	79.76	7.67	7.15	102.69	8.28	570.47	618.28	7.73
35.9	84.68	83.36	7.63	7.29	106.33	8.19	607.68	642.32	5.39
58.2	75.93	73.41	7.72	7.19	97.44	8.40	527.85	584.96	9.76
61.2	74.72	71.72	7.74	7.24	96.21	8.43	519.26	577.38	10.07
40.7	82.81	81.56	7.65	7.20	104.43	8.24	587.36	629.67	6.72
55.2	77.09	74.96	7.71	7.16	98.62	8.37	536.54	592.33	9.42
50.7	78.86	77.19	7.69	7.13	100.42	8.33	550.70	603.70	8.78
61.8	74.48	71.38	7.74	7.25	95.97	8.44	517.61	575.89	10.12
56.0	76.78	74.55	7.71	7.17	98.30	8.38	534.15	590.33	9.52
54.2	77.49	75.48	7.71	7.15	99.03	8.36	539.64	594.89	9.29
41.6	82.44	81.19	7.65	7.19	104.05	8.25	583.59	627.20	6.95
37.9	83.89	82.63	7.64	7.25	105.53	8.21	598.91	636.99	5.98
42.9	81.94	80.67	7.66	7.17	103.55	8.26	578.63	623.89	7.25
47.1	80.28	78.86	7.68	7.14	101.87	8.30	563.04	612.97	8.14
38.8	83.53	82.28	7.64	7.23	105.16	8.22	594.97	634.54	6.23
47.0	80.30	78.87	7.68	7.14	101.88	8.30	563.16	613.05	8.14
38.8	83.53	82.28	7.64	7.23	105.17	8.22	595.01	634.56	6.23
29.4	87.26	85.54	7.60	7.47	108.95	8.13	639.15	660.08	3.17
28.7	87.52	85.74	7.60	7.49	109.22	8.13	642.56	661.90	2.92
58.1	75.96	73.45	7.72	7.19	97.47	8.40	528.07	585.15	9.75
55.4	77.00	74.84	7.71	7.16	98.53	8.38	535.86	591.76	9.45
26.2	88.48	86.45	7.59	7.58	110.20	8.10	655.58	668.66	1.96
50.9	78.77	77.07	7.69	7.14	100.32	8.33	549.90	603.08	8.82
33.2	85.75	84.31	7.62	7.36	107.42	8.17	620.31	649.69	4.52
59.6	75.37	72.65	7.73	7.21	96.88	8.42	523.89	581.49	9.91

64.9	73.27	69.61	7.75	7.32	94.74	8.47	509.47	568.45	10.38
39.2	83.38	82.13	7.64	7.22	105.01	8.22	593.38	633.53	6.34
58.1	75.94	73.42	7.72	7.19	97.45	8.40	527.92	585.01	9.76
64.4	73.48	69.91	7.75	7.31	94.95	8.46	510.82	569.70	10.33
62.4	74.25	71.05	7.74	7.26	95.73	8.44	516.03	574.46	10.17
29.8	87.06	85.39	7.60	7.46	108.76	8.14	636.65	658.74	3.35
28.0	87.78	85.94	7.59	7.52	109.48	8.12	646.02	663.72	2.67
34.6	85.18	83.81	7.62	7.32	106.84	8.18	613.51	645.76	4.99
55.4	77.01	74.86	7.71	7.16	98.54	8.38	535.96	591.85	9.44
48.5	79.74	78.24	7.68	7.14	101.32	8.31	558.25	609.43	8.40
41.4	82.53	81.29	7.65	7.19	104.15	8.24	584.58	627.86	6.89
59.6	75.37	72.64	7.73	7.21	96.87	8.42	523.86	581.46	9.91
38.6	83.61	82.35	7.64	7.23	105.24	8.22	595.81	635.06	6.18
33.1	85.79	84.34	7.62	7.36	107.46	8.17	620.73	649.92	4.49
37.4	84.09	82.82	7.63	7.26	105.74	8.21	601.13	638.36	5.83
42.2	82.22	80.97	7.65	7.18	103.83	8.25	581.43	625.77	7.09
44.3	81.36	80.05	7.66	7.16	102.96	8.27	573.02	620.05	7.59
33.2	85.73	84.29	7.62	7.36	107.40	8.17	620.04	649.53	4.54
44.7	81.21	79.89	7.67	7.15	102.80	8.28	571.57	619.04	7.67
38.8	83.53	82.28	7.64	7.23	105.17	8.22	595.01	634.56	6.23
38.5	83.68	82.42	7.64	7.24	105.31	8.22	596.57	635.53	6.13
44.3	81.37	80.06	7.66	7.16	102.97	8.27	573.09	620.10	7.58
46.0	80.71	79.34	7.67	7.15	102.30	8.29	566.92	615.76	7.93
27.5	87.99	86.09	7.59	7.54	109.69	8.12	648.79	665.16	2.46
58.4	75.83	73.28	7.72	7.19	97.34	8.40	527.17	584.37	9.79
62.2	74.34	71.18	7.74	7.26	95.83	8.44	516.67	575.04	10.15
64.3	73.52	69.97	7.75	7.30	94.99	8.46	511.08	569.93	10.33
26.7	88.30	86.32	7.59	7.57	110.01	8.11	653.08	667.38	2.14
47.5	80.11	78.66	7.68	7.14	101.69	8.30	561.47	611.81	8.23
44.7	81.20	79.88	7.67	7.15	102.80	8.28	571.54	619.02	7.67
53.0	77.96	76.08	7.70	7.14	99.51	8.35	543.35	597.90	9.12
55.7	76.90	74.71	7.71	7.16	98.43	8.38	535.06	591.10	9.48
34.6	85.20	83.83	7.62	7.32	106.86	8.18	613.70	645.87	4.98
39.5	83.29	82.04	7.64	7.22	104.92	8.23	592.39	632.90	6.40
26.9	88.23	86.27	7.59	7.56	109.93	8.11	652.04	666.85	2.22
51.6	78.50	76.75	7.70	7.14	100.06	8.34	547.72	601.38	8.92
52.8	78.03	76.16	7.70	7.14	99.57	8.35	543.89	598.33	9.10
52.5	78.14	76.30	7.70	7.14	99.69	8.35	544.81	599.07	9.06
44.8	81.16	79.84	7.67	7.15	102.76	8.28	571.15	618.75	7.69
33.9	85.48	84.07	7.62	7.34	107.14	8.18	616.98	647.78	4.75
52.2	78.25	76.44	7.70	7.14	99.80	8.35	545.71	599.78	9.02
58.9	75.63	73.00	7.73	7.20	97.14	8.41	525.69	583.08	9.84
55.7	76.90	74.71	7.71	7.16	98.43	8.38	535.10	591.13	9.48

38.3	83.76	82.50	7.64	7.24	105.40	8.22	597.44	636.08	6.07
44.4	81.35	80.05	7.66	7.16	102.95	8.27	572.94	620.00	7.59
31.0	86.59	85.01	7.61	7.42	108.28	8.15	630.65	655.47	3.79
46.3	80.59	79.20	7.67	7.14	102.18	8.29	565.82	614.97	7.99
58.5	75.79	73.22	7.73	7.20	97.30	8.41	526.84	584.07	9.80
37.1	84.21	82.93	7.63	7.26	105.86	8.20	602.45	639.16	5.74
61.1	74.79	71.83	7.74	7.24	96.28	8.43	519.77	577.84	10.05
59.0	75.61	72.98	7.73	7.20	97.12	8.41	525.58	582.98	9.85
35.4	84.88	83.55	7.63	7.30	106.54	8.19	610.04	643.72	5.23
60.9	74.84	71.89	7.74	7.23	96.33	8.43	520.10	578.13	10.04
38.3	83.73	82.47	7.64	7.24	105.37	8.22	597.15	635.90	6.09
36.4	84.49	83.19	7.63	7.28	106.14	8.20	605.61	641.08	5.53
25.8	88.64	86.56	7.58	7.60	110.35	8.10	657.73	669.75	1.79
50.9	78.77	77.08	7.69	7.13	100.33	8.33	549.95	603.11	8.82
57.5	76.18	73.75	7.72	7.18	97.70	8.40	529.71	586.55	9.69
60.3	75.07	72.22	7.73	7.22	96.57	8.42	521.71	579.57	9.98
28.6	87.55	85.76	7.60	7.50	109.24	8.13	642.93	662.10	2.89
56.6	76.56	74.26	7.72	7.17	98.08	8.39	532.53	588.96	9.58
57.2	76.32	73.94	7.72	7.18	97.84	8.39	530.72	587.42	9.65
63.5	73.81	70.40	7.75	7.29	95.29	8.45	513.05	571.74	10.27
35.7	84.77	83.44	7.63	7.29	106.42	8.19	608.69	642.92	5.32
37.4	84.11	82.83	7.63	7.26	105.75	8.21	601.30	638.46	5.82
42.1	82.25	81.00	7.65	7.18	103.86	8.25	581.71	625.95	7.07
44.7	81.22	79.91	7.67	7.15	102.82	8.28	571.73	619.16	7.66
44.1	81.45	80.15	7.66	7.16	103.05	8.27	573.88	620.65	7.54
50.4	78.98	77.33	7.69	7.13	100.54	8.33	551.68	604.45	8.73
48.6	79.70	78.18	7.68	7.14	101.27	8.31	557.83	609.12	8.42
38.8	83.54	82.29	7.64	7.23	105.18	8.22	595.13	634.63	6.23
31.0	86.60	85.01	7.61	7.42	108.28	8.15	630.68	655.49	3.78
51.4	78.59	76.86	7.69	7.14	100.14	8.34	548.44	601.94	8.89
26.5	88.39	86.38	7.59	7.57	110.10	8.11	654.27	667.99	2.05
45.9	80.76	79.39	7.67	7.15	102.35	8.29	567.35	616.07	7.91
61.3	74.68	71.67	7.74	7.24	96.18	8.43	519.02	577.16	10.07
37.0	84.23	82.95	7.63	7.27	105.88	8.20	602.68	639.30	5.73
29.9	87.03	85.36	7.60	7.45	108.72	8.14	636.17	658.48	3.39
64.0	73.65	70.17	7.75	7.30	95.13	8.46	511.98	570.76	10.30
26.3	88.46	86.44	7.59	7.58	110.17	8.11	655.25	668.49	1.98
51.0	78.72	77.02	7.69	7.14	100.28	8.34	549.56	602.82	8.83
33.3	85.72	84.28	7.62	7.35	107.39	8.17	619.86	649.43	4.55
45.1	81.07	79.73	7.67	7.15	102.66	8.28	570.22	618.10	7.75
62.1	74.39	71.24	7.74	7.26	95.87	8.44	516.97	575.32	10.14
57.0	76.37	74.01	7.72	7.18	97.89	8.39	531.14	587.78	9.64
60.1	75.16	72.35	7.73	7.22	96.66	8.42	522.39	580.17	9.96

46.9	80.37	78.95	7.68	7.14	101.95	8.30	563.80	613.51	8.10
42.7	81.99	80.73	7.66	7.17	103.60	8.26	579.15	624.24	7.22
59.0	75.58	72.94	7.73	7.20	97.09	8.41	525.38	582.81	9.85
43.0	81.89	80.62	7.66	7.17	103.50	8.26	578.19	623.60	7.28
51.9	78.38	76.60	7.70	7.14	99.93	8.34	546.75	600.61	8.97
64.0	73.65	70.17	7.75	7.30	95.13	8.46	511.98	570.76	10.30
32.0	86.22	84.70	7.61	7.39	107.89	8.16	625.94	652.86	4.12
37.0	84.25	82.97	7.63	7.27	105.90	8.20	602.89	639.43	5.71
26.8	88.25	86.29	7.59	7.56	109.96	8.11	652.39	667.03	2.19
40.8	82.77	81.53	7.65	7.20	104.39	8.24	587.01	629.44	6.74
45.3	80.98	79.64	7.67	7.15	102.57	8.28	569.40	617.52	7.79
29.8	87.09	85.41	7.60	7.46	108.78	8.14	637.01	658.93	3.33
39.2	83.40	82.15	7.64	7.23	105.03	8.22	593.60	633.67	6.32
44.1	81.44	80.14	7.66	7.16	103.04	8.27	573.77	620.57	7.54
27.2	88.10	86.18	7.59	7.55	109.81	8.11	650.37	665.98	2.34
59.5	75.40	72.68	7.73	7.21	96.91	8.42	524.07	581.65	9.90
59.1	75.57	72.92	7.73	7.20	97.08	8.41	525.30	582.73	9.86
37.5	84.07	82.80	7.63	7.26	105.71	8.21	600.87	638.20	5.85
29.5	87.19	85.48	7.60	7.47	108.88	8.13	638.23	659.59	3.24
30.4	86.86	85.23	7.60	7.44	108.55	8.14	634.08	657.35	3.54
61.2	74.71	71.72	7.74	7.24	96.21	8.43	519.24	577.36	10.07
47.9	79.96	78.49	7.68	7.14	101.54	8.31	560.19	610.87	8.30
42.7	81.99	80.73	7.66	7.17	103.60	8.26	579.14	624.24	7.22
41.1	82.65	81.41	7.65	7.20	104.27	8.24	585.76	628.63	6.82
58.8	75.67	73.06	7.73	7.20	97.18	8.41	526.02	583.36	9.83
64.6	73.40	69.80	7.75	7.31	94.87	8.46	510.31	569.23	10.35
35.2	84.96	83.61	7.62	7.31	106.61	8.19	610.88	644.22	5.17
28.1	87.74	85.91	7.59	7.51	109.44	8.12	645.49	663.44	2.71
51.5	78.56	76.82	7.69	7.14	100.11	8.34	548.17	601.73	8.90
48.6	79.70	78.18	7.68	7.14	101.27	8.31	557.86	609.15	8.42
55.3	77.05	74.91	7.71	7.16	98.58	8.38	536.23	592.08	9.43
64.3	73.50	69.95	7.75	7.31	94.98	8.46	510.99	569.85	10.33
61.5	74.60	71.56	7.74	7.25	96.09	8.43	518.47	576.67	10.09
60.4	75.06	72.20	7.73	7.22	96.56	8.42	521.65	579.51	9.98
64.8	73.30	69.65	7.75	7.32	94.77	8.47	509.67	568.63	10.37
30.6	86.76	85.14	7.61	7.43	108.44	8.14	632.72	656.61	3.64
60.5	74.99	72.11	7.73	7.23	96.49	8.43	521.17	579.08	10.00
47.0	80.33	78.91	7.68	7.14	101.91	8.30	563.41	613.23	8.12
44.9	81.12	79.80	7.67	7.15	102.72	8.28	570.77	618.49	7.71
37.9	83.91	82.64	7.64	7.25	105.55	8.21	599.10	637.10	5.97
56.3	76.66	74.40	7.72	7.17	98.19	8.38	533.30	589.62	9.55
61.9	74.45	71.33	7.74	7.25	95.94	8.44	517.39	575.69	10.13
32.7	85.96	84.48	7.61	7.37	107.63	8.16	622.77	651.08	4.35

63.0	74.03	70.73	7.74	7.27	95.51	8.45	514.56	573.12	10.22
32.4	86.05	84.56	7.61	7.38	107.73	8.16	623.93	651.74	4.27
30.4	86.86	85.23	7.60	7.44	108.55	8.14	634.05	657.33	3.54
52.7	78.07	76.22	7.70	7.14	99.62	8.35	544.24	598.62	9.08
62.3	74.29	71.11	7.74	7.26	95.78	8.44	516.35	574.75	10.16
51.8	78.43	76.66	7.70	7.14	99.98	8.34	547.15	600.92	8.95
34.8	85.10	83.74	7.62	7.32	106.76	8.18	612.58	645.22	5.06
37.5	84.05	82.78	7.63	7.26	105.69	8.21	600.62	638.04	5.87
50.1	79.08	77.46	7.69	7.13	100.65	8.33	552.57	605.14	8.69
49.3	79.42	77.85	7.69	7.13	100.99	8.32	555.41	607.30	8.54
63.8	73.72	70.27	7.75	7.29	95.19	8.46	512.43	571.17	10.29
46.8	80.41	79.00	7.67	7.14	101.99	8.29	564.14	613.76	8.09
54.3	77.45	75.43	7.71	7.15	98.99	8.37	539.32	594.63	9.30
41.1	82.63	81.38	7.65	7.19	104.25	8.24	585.51	628.47	6.84
44.4	81.33	80.02	7.66	7.16	102.93	8.27	572.69	619.83	7.60
56.2	76.70	74.44	7.72	7.17	98.22	8.38	533.54	589.82	9.54
32.4	86.04	84.55	7.61	7.38	107.72	8.16	623.80	651.66	4.28
31.0	86.63	85.04	7.61	7.42	108.31	8.15	631.07	655.71	3.76
48.0	79.91	78.43	7.68	7.14	101.49	8.31	559.70	610.51	8.32
39.4	83.32	82.08	7.64	7.22	104.95	8.23	592.78	633.15	6.38
43.1	81.85	80.58	7.66	7.17	103.46	8.26	577.73	623.29	7.31
34.6	85.20	83.83	7.62	7.32	106.86	8.18	613.71	645.88	4.98
38.7	83.58	82.33	7.64	7.23	105.22	8.22	595.56	634.91	6.20
42.0	82.27	81.02	7.65	7.18	103.89	8.25	581.95	626.12	7.05
46.3	80.60	79.21	7.67	7.14	102.18	8.29	565.88	615.01	7.99
47.9	79.96	78.49	7.68	7.14	101.54	8.31	560.17	610.86	8.30
34.3	85.31	83.93	7.62	7.33	106.98	8.18	615.04	646.65	4.89
47.7	80.03	78.56	7.68	7.14	101.60	8.30	560.74	611.28	8.27
52.5	78.16	76.33	7.70	7.14	99.71	8.35	544.97	599.20	9.05
31.3	86.51	84.94	7.61	7.41	108.19	8.15	629.55	654.86	3.87
51.5	78.54	76.79	7.70	7.14	100.09	8.34	548.03	601.62	8.91
56.6	76.55	74.25	7.72	7.17	98.08	8.39	532.48	588.92	9.58
63.4	73.86	70.48	7.75	7.28	95.34	8.45	513.42	572.08	10.25
43.5	81.69	80.40	7.66	7.17	103.29	8.26	576.15	622.20	7.40
31.8	86.29	84.76	7.61	7.40	107.97	8.16	626.86	653.37	4.06
62.8	74.11	70.85	7.74	7.27	95.59	8.45	515.10	573.61	10.20
58.7	75.73	73.14	7.73	7.20	97.24	8.41	526.42	583.71	9.81
33.9	85.49	84.08	7.62	7.34	107.15	8.17	617.10	647.85	4.75
28.5	87.59	85.79	7.60	7.50	109.29	8.13	643.52	662.40	2.85
60.8	74.89	71.96	7.73	7.23	96.38	8.43	520.45	578.44	10.03
28.2	87.73	85.90	7.59	7.51	109.43	8.12	645.32	663.35	2.72
39.9	83.12	81.88	7.64	7.21	104.75	8.23	590.68	631.81	6.51
52.1	78.29	76.49	7.70	7.14	99.84	8.35	546.02	600.03	9.00

37.7	83.97	82.70	7.64	7.25	105.61	8.21	599.76	637.51	5.92
47.4	80.18	78.74	7.68	7.14	101.76	8.30	562.09	612.27	8.20
61.6	74.59	71.53	7.74	7.25	96.08	8.43	518.35	576.56	10.10
41.6	82.46	81.21	7.65	7.19	104.07	8.25	583.79	627.34	6.94
64.0	73.63	70.14	7.75	7.30	95.11	8.46	511.86	570.65	10.30
60.6	74.95	72.05	7.73	7.23	96.45	8.43	520.90	578.85	10.01
50.7	78.85	77.18	7.69	7.13	100.41	8.33	550.62	603.64	8.78
30.3	86.87	85.23	7.60	7.44	108.56	8.14	634.17	657.39	3.53
55.3	77.04	74.89	7.71	7.16	98.57	8.38	536.12	591.98	9.44
53.3	77.84	75.92	7.70	7.14	99.38	8.36	542.36	597.10	9.17
28.3	87.68	85.87	7.60	7.51	109.38	8.12	644.75	663.05	2.76
53.1	77.91	76.00	7.70	7.14	99.45	8.35	542.90	597.54	9.14
49.7	79.24	77.64	7.69	7.13	100.81	8.32	553.91	606.17	8.62
45.0	81.12	79.79	7.67	7.15	102.71	8.28	570.72	618.45	7.72
52.2	78.26	76.45	7.70	7.14	99.81	8.35	545.74	599.81	9.01
53.4	77.81	75.88	7.70	7.14	99.35	8.36	542.13	596.91	9.18
46.9	80.37	78.95	7.68	7.14	101.95	8.30	563.80	613.52	8.10
56.3	76.65	74.38	7.72	7.17	98.17	8.38	533.20	589.53	9.55
27.1	88.15	86.21	7.59	7.55	109.86	8.11	651.01	666.31	2.30
31.8	86.29	84.76	7.61	7.40	107.97	8.16	626.83	653.36	4.06
36.6	84.43	83.13	7.63	7.28	106.07	8.20	604.83	640.61	5.58
52.1	78.30	76.50	7.70	7.14	99.85	8.35	546.06	600.06	9.00
61.8	74.50	71.41	7.74	7.25	95.99	8.44	517.78	576.04	10.11
52.5	78.16	76.33	7.70	7.14	99.71	8.35	544.96	599.19	9.05
64.2	73.56	70.04	7.75	7.30	95.04	8.46	511.39	570.22	10.32
28.9	87.43	85.67	7.60	7.49	109.13	8.13	641.40	661.28	3.01
42.7	82.01	80.74	7.66	7.17	103.62	8.26	579.30	624.34	7.21
63.8	73.72	70.27	7.75	7.29	95.19	8.46	512.43	571.18	10.29
59.7	75.32	72.57	7.73	7.21	96.82	8.42	523.50	581.15	9.92
30.0	87.01	85.34	7.60	7.45	108.70	8.14	635.94	658.36	3.40
48.2	79.85	78.36	7.68	7.14	101.42	8.31	559.14	610.10	8.35
59.4	75.45	72.75	7.73	7.21	96.95	8.41	524.41	581.95	9.89
53.4	77.81	75.88	7.70	7.14	99.35	8.36	542.14	596.92	9.18
26.6	88.33	86.34	7.59	7.57	110.04	8.11	653.51	667.60	2.11
31.5	86.41	84.86	7.61	7.40	108.09	8.15	628.32	654.18	3.95
62.8	74.10	70.83	7.74	7.27	95.59	8.45	515.04	573.56	10.20
31.6	86.37	84.82	7.61	7.40	108.05	8.15	627.81	653.90	3.99
30.3	86.90	85.26	7.60	7.44	108.59	8.14	634.52	657.58	3.51
36.7	84.35	83.06	7.63	7.27	106.00	8.20	604.03	640.13	5.64
26.8	88.25	86.29	7.59	7.56	109.96	8.11	652.40	667.03	2.19
60.6	74.96	72.07	7.73	7.23	96.46	8.43	520.98	578.92	10.01
54.2	77.49	75.48	7.71	7.15	99.03	8.36	539.64	594.89	9.29
62.4	74.27	71.08	7.74	7.26	95.76	8.44	516.19	574.61	10.17

48.0	79.94	78.46	7.68	7.14	101.52	8.31	559.98	610.72	8.31
63.5	73.84	70.45	7.75	7.29	95.32	8.45	513.24	571.92	10.26
48.6	79.68	78.16	7.68	7.14	101.25	8.31	557.67	609.00	8.43
59.6	75.36	72.63	7.73	7.21	96.86	8.42	523.77	581.39	9.91
43.3	81.76	80.49	7.66	7.17	103.37	8.26	576.91	622.73	7.36
36.4	84.50	83.20	7.63	7.28	106.15	8.20	605.70	641.13	5.53
52.3	78.22	76.40	7.70	7.14	99.77	8.35	545.46	599.58	9.03
54.8	77.26	75.18	7.71	7.15	98.79	8.37	537.84	593.41	9.36
26.7	88.30	86.32	7.59	7.57	110.01	8.11	653.11	667.40	2.14

Case 2: Varying Irradiance

Irradiance	Vmp_pre	Vmp_actual	Imp_pre	Imp_actual	Voc	Isc	Pmp_actual	%-error
0.5787	89.8268	84.13	4.41	3.90	108.51	4.69	327.71	16.78
0.1935	86.2448	80.23	1.48	1.18	101.56	1.57	94.37	27.69
0.0972	84.6233	79.20	0.74	0.56	99.04	0.79	44.33	30.31
0.5074	89.5147	83.44	3.87	3.36	107.60	4.11	280.48	18.84
0.5246	89.6045	83.60	4.00	3.49	107.84	4.25	291.69	18.35
0.3648	88.4122	82.01	2.79	2.34	105.26	2.96	191.54	22.91
0.2304	86.7893	80.62	1.77	1.42	102.44	1.87	114.42	26.67
0.4733	89.3091	83.10	3.62	3.11	107.10	3.83	258.54	19.82
0.9096	89.1892	87.18	6.89	6.55	110.53	7.36	571.15	7.01
0.7368	89.9502	85.62	5.60	5.13	109.93	5.96	438.99	12.16
0.1129	84.9070	79.37	0.86	0.66	99.47	0.91	52.25	29.89
0.4108	88.8373	82.48	3.14	2.66	106.09	3.33	219.42	21.61
0.8012	89.7761	86.21	6.08	5.65	110.27	6.48	486.94	10.25
0.6901	89.9952	85.19	5.25	4.76	109.60	5.59	405.19	13.53
0.8083	89.7490	86.27	6.14	5.71	110.30	6.54	492.32	10.04
0.5984	89.8849	84.32	4.56	4.05	108.74	4.85	341.09	16.21
1.0318	88.0854	88.23	7.80	7.61	110.35	8.35	671.31	3.32
0.7357	89.9521	85.61	5.59	5.12	109.93	5.96	438.19	12.19
0.9513	88.8649	87.54	7.20	6.91	110.53	7.70	604.73	5.76
0.7167	89.9779	85.43	5.45	4.97	109.80	5.80	424.37	12.75
0.0808	84.3174	79.02	0.62	0.46	98.58	0.65	36.12	30.75
0.8754	89.4140	86.88	6.64	6.26	110.49	7.08	544.13	8.04
0.1091	84.8394	79.33	0.83	0.63	99.37	0.88	50.34	29.99
0.9433	88.9318	87.47	7.14	6.84	110.53	7.63	598.19	6.00
0.8824	89.3708	86.94	6.69	6.32	110.50	7.14	549.65	7.83
0.7896	89.8169	86.10	6.00	5.55	110.22	6.39	478.21	10.60
0.1527	85.5931	79.79	1.17	0.91	100.53	1.24	72.77	28.81
0.7086	89.9856	85.36	5.39	4.90	109.74	5.74	418.48	12.99
0.0743	84.1942	78.95	0.57	0.42	98.40	0.60	32.89	30.92

0.1885	86.1688	80.18	1.44	1.14	101.44	1.53	91.73	27.83
0.5548	89.7399	83.90	4.23	3.71	108.23	4.49	311.66	17.48
0.0612	83.9414	78.80	0.47	0.34	98.02	0.50	26.43	31.26
1.0490	87.8925	88.38	7.93	7.76	110.29	8.49	685.85	2.80
0.2185	86.6184	80.49	1.67	1.34	102.16	1.77	107.90	27.00
0.4820	89.3649	83.19	3.68	3.17	107.23	3.90	264.09	19.57
0.5734	89.8089	84.08	4.37	3.85	108.45	4.64	324.10	16.94
0.9399	88.9589	87.44	7.12	6.81	110.53	7.60	595.49	6.10
1.0009	88.4091	87.97	7.57	7.34	110.44	8.10	645.43	4.26
0.1107	84.8684	79.34	0.85	0.64	99.42	0.90	51.16	29.95
0.2293	86.7747	80.61	1.76	1.41	102.41	1.86	113.85	26.70
0.9813	88.5985	87.80	7.42	7.17	110.49	7.94	629.23	4.85
0.4688	89.2788	83.05	3.58	3.08	107.03	3.80	255.64	19.95
0.4833	89.3730	83.20	3.69	3.18	107.25	3.91	264.91	19.54
0.5695	89.7954	84.04	4.34	3.83	108.41	4.61	321.50	17.05
0.7440	89.9372	85.69	5.66	5.18	109.98	6.02	444.27	11.95
0.2613	87.2136	80.94	2.00	1.63	103.14	2.12	131.62	25.81
0.4725	89.3034	83.09	3.61	3.10	107.09	3.83	257.99	19.85
0.3740	88.5029	82.10	2.86	2.40	105.43	3.03	197.08	22.65
0.3496	88.2569	81.85	2.68	2.23	104.97	2.83	182.49	23.34
0.1994	86.3353	80.29	1.53	1.22	101.70	1.62	97.56	27.53
0.7034	89.9894	85.31	5.35	4.86	109.70	5.69	414.70	13.14
0.3044	87.7531	81.39	2.33	1.92	104.07	2.47	156.09	24.61
0.6016	89.8932	84.35	4.59	4.07	108.77	4.87	343.26	16.12
0.2062	86.4377	80.36	1.58	1.26	101.87	1.67	101.24	27.34
0.9035	89.2319	87.12	6.85	6.50	110.53	7.31	566.31	7.20
0.1337	85.2721	79.59	1.02	0.79	100.03	1.08	62.92	29.33
0.8852	89.3534	86.96	6.71	6.35	110.51	7.16	551.82	7.75
0.3428	88.1857	81.79	2.62	2.18	104.84	2.78	178.50	23.53
0.2012	86.3620	80.31	1.54	1.23	101.74	1.63	98.51	27.48
0.5563	89.7457	83.91	4.24	3.73	108.25	4.50	312.63	17.43
0.8385	89.6153	86.55	6.36	5.96	110.41	6.79	515.50	9.14
1.0228	88.1830	88.16	7.73	7.53	110.38	8.27	663.72	3.59
0.5726	89.8063	84.07	4.37	3.85	108.44	4.64	323.60	16.96
0.5418	89.6849	83.77	4.13	3.62	108.06	4.39	302.99	17.85
0.5366	89.6615	83.72	4.09	3.58	107.99	4.35	299.55	18.00
0.8082	89.7491	86.27	6.14	5.71	110.30	6.54	492.30	10.04
0.7863	89.8277	86.07	5.97	5.53	110.21	6.36	475.77	10.69
0.0931	84.5470	79.15	0.71	0.53	98.93	0.75	42.25	30.42
0.9605	88.7863	87.62	7.27	6.99	110.52	7.77	612.20	5.48
0.1062	84.7865	79.29	0.81	0.62	99.29	0.86	48.85	30.07
0.7706	89.8750	85.93	5.86	5.40	110.13	6.24	463.98	11.16
1.0214	88.1979	88.15	7.72	7.52	110.39	8.26	662.55	3.64

0.2749	87.3894	81.08	2.11	1.72	103.44	2.23	139.24	25.43
0.2257	86.7233	80.57	1.73	1.39	102.33	1.83	111.87	26.80
0.9544	88.8388	87.57	7.23	6.93	110.52	7.72	607.24	5.66
0.4112	88.8409	82.48	3.14	2.66	106.10	3.33	219.67	21.60
0.0468	83.6588	78.65	0.35	0.25	97.60	0.38	19.44	31.62
0.7830	89.8383	86.04	5.95	5.50	110.19	6.34	473.28	10.79
0.5171	89.5663	83.53	3.95	3.43	107.73	4.19	286.77	18.57
0.3695	88.4588	82.06	2.83	2.37	105.35	2.99	194.37	22.78
1.0019	88.3993	87.98	7.58	7.35	110.44	8.10	646.24	4.23
0.4309	89.0022	82.68	3.29	2.80	106.43	3.49	231.83	21.04
0.7364	89.9508	85.62	5.60	5.12	109.93	5.96	438.72	12.17
0.0586	83.8906	78.78	0.45	0.32	97.95	0.47	25.16	31.33
0.3118	87.8404	81.47	2.39	1.97	104.22	2.53	160.38	24.40
0.8390	89.6133	86.55	6.37	5.96	110.41	6.79	515.81	9.13
0.6825	89.9961	85.12	5.19	4.70	109.54	5.53	399.76	13.76
0.8556	89.5276	86.70	6.49	6.10	110.45	6.92	528.65	8.63
0.1013	84.6977	79.24	0.77	0.59	99.16	0.82	46.38	30.20
0.0958	84.5981	79.18	0.73	0.55	99.01	0.78	43.64	30.35
0.5243	89.6029	83.60	4.00	3.49	107.83	4.25	291.48	18.36
0.6241	89.9424	84.56	4.76	4.24	109.01	5.05	358.74	15.46
0.2952	87.6428	81.30	2.26	1.86	103.88	2.39	150.81	24.87
0.8833	89.3653	86.95	6.70	6.33	110.51	7.15	550.34	7.80
0.1454	85.4709	79.72	1.11	0.87	100.34	1.18	68.96	29.01
0.3532	88.2943	81.89	2.70	2.25	105.04	2.86	184.62	23.24
0.1626	85.7562	79.90	1.25	0.98	100.78	1.32	77.96	28.54
0.7620	89.8976	85.85	5.79	5.33	110.08	6.17	457.56	11.42
0.0514	83.7505	78.70	0.39	0.28	97.74	0.42	21.68	31.51
0.0588	83.8961	78.78	0.45	0.32	97.96	0.48	25.30	31.32
1.0217	88.1944	88.15	7.72	7.52	110.39	8.27	662.82	3.63
0.2956	87.6477	81.30	2.26	1.86	103.88	2.39	151.04	24.85
0.8915	89.3125	87.02	6.76	6.40	110.52	7.21	556.83	7.56
0.6016	89.8930	84.35	4.59	4.07	108.77	4.87	343.21	16.12
0.4958	89.4485	83.32	3.79	3.28	107.44	4.02	272.93	19.18
0.0063	82.8258	78.20	0.04	0.00	96.39	0.05	0.07	-21.03
0.6419	89.9701	84.73	4.89	4.38	109.18	5.20	371.09	14.95
0.6901	89.9953	85.19	5.25	4.76	109.60	5.59	405.17	13.53
1.0294	88.1116	88.21	7.78	7.59	110.36	8.33	669.29	3.39
0.4516	89.1595	82.88	3.45	2.95	106.77	3.66	244.82	20.44
0.2143	86.5580	80.45	1.64	1.31	102.06	1.74	105.65	27.12
0.8350	89.6324	86.51	6.34	5.93	110.40	6.76	512.77	9.25
0.5110	89.5343	83.47	3.90	3.39	107.65	4.14	282.82	18.74
0.6852	89.9960	85.14	5.22	4.72	109.56	5.55	401.68	13.68
0.4979	89.4608	83.34	3.80	3.29	107.47	4.03	274.29	19.12

0.3092	87.8095	81.44	2.37	1.95	104.17	2.50	158.85	24.48
0.7299	89.9612	85.56	5.55	5.07	109.89	5.91	433.95	12.36
0.1735	85.9328	80.02	1.33	1.05	101.06	1.41	83.74	28.24
0.6988	89.9921	85.27	5.32	4.82	109.67	5.66	411.38	13.28
0.7692	89.8788	85.92	5.84	5.39	110.12	6.23	462.94	11.20
0.5116	89.5374	83.48	3.91	3.39	107.66	4.14	283.20	18.72
0.9029	89.2358	87.12	6.84	6.50	110.53	7.31	565.86	7.21
0.8486	89.5643	86.64	6.44	6.04	110.44	6.87	523.30	8.84
0.1504	85.5558	79.77	1.15	0.90	100.47	1.22	71.60	28.87
0.6225	89.9393	84.55	4.74	4.23	108.99	5.04	357.59	15.51
0.8600	89.5033	86.74	6.52	6.13	110.46	6.96	532.11	8.50
0.9394	88.9634	87.44	7.11	6.81	110.53	7.60	595.05	6.12
0.2043	86.4095	80.34	1.57	1.25	101.82	1.66	100.22	27.39
0.8352	89.6317	86.52	6.34	5.93	110.40	6.76	512.89	9.24
1.0054	88.3633	88.01	7.60	7.38	110.43	8.13	649.22	4.12
0.9282	89.0510	87.34	7.03	6.71	110.54	7.51	586.08	6.45
0.8713	89.4386	86.84	6.61	6.23	110.49	7.05	540.91	8.16
0.7212	89.9728	85.48	5.49	5.00	109.83	5.84	427.62	12.62
0.8560	89.5251	86.70	6.49	6.10	110.45	6.93	529.02	8.62
0.3702	88.4656	82.07	2.83	2.37	105.36	3.00	194.78	22.76
0.0731	84.1708	78.93	0.56	0.41	98.36	0.59	32.29	30.95
0.3387	88.1415	81.74	2.59	2.15	104.76	2.74	176.07	23.65
0.8225	89.6896	86.40	6.24	5.82	110.36	6.66	503.20	9.62
0.9268	89.0618	87.33	7.02	6.70	110.54	7.50	584.95	6.49
0.3787	88.5477	82.15	2.90	2.43	105.52	3.07	199.89	22.52
0.2667	87.2844	81.00	2.04	1.66	103.26	2.16	134.65	25.66
0.1679	85.8428	79.96	1.29	1.01	100.92	1.36	80.77	28.39
0.2529	87.1010	80.86	1.94	1.57	102.95	2.05	126.90	26.05
0.1972	86.3011	80.27	1.51	1.20	101.65	1.60	96.35	27.59
0.0053	82.8032	78.19	0.03	-0.01	96.35	0.04	-0.43	37.18
0.8473	89.5713	86.63	6.43	6.03	110.43	6.86	522.26	8.88
0.7359	89.9517	85.61	5.60	5.12	109.93	5.96	438.35	12.19
0.4981	89.4624	83.34	3.80	3.29	107.47	4.03	274.47	19.11
0.8638	89.4818	86.77	6.55	6.17	110.47	6.99	535.09	8.39
0.1279	85.1712	79.53	0.98	0.75	99.88	1.04	59.92	29.48
0.5283	89.6223	83.64	4.03	3.52	107.89	4.28	294.08	18.24
0.0873	84.4395	79.09	0.67	0.50	98.77	0.71	39.36	30.58
0.6526	89.9820	84.83	4.97	4.46	109.28	5.28	378.61	14.63
0.9042	89.2269	87.13	6.85	6.51	110.53	7.32	566.89	7.17
0.4658	89.2591	83.03	3.56	3.06	106.99	3.77	253.78	20.04
0.2781	87.4310	81.12	2.13	1.74	103.51	2.25	141.09	25.34
0.2028	86.3863	80.33	1.55	1.24	101.78	1.64	99.38	27.43
1.0217	88.1949	88.15	7.72	7.52	110.39	8.26	662.78	3.63

0.9880	88.5353	87.86	7.47	7.22	110.47	7.99	634.74	4.65
0.5109	89.5338	83.47	3.90	3.39	107.65	4.14	282.76	18.74
0.2469	87.0191	80.79	1.89	1.53	102.82	2.00	123.54	26.21
0.6289	89.9507	84.61	4.79	4.28	109.06	5.09	362.01	15.33
0.2144	86.5586	80.45	1.64	1.31	102.06	1.74	105.67	27.11
0.2181	86.6131	80.49	1.67	1.34	102.15	1.77	107.70	27.01
0.6899	89.9953	85.18	5.25	4.75	109.60	5.59	405.05	13.54
0.4452	89.1121	82.82	3.40	2.91	106.66	3.61	240.77	20.63
0.2192	86.6294	80.50	1.68	1.35	102.18	1.78	108.31	26.98
0.8059	89.7581	86.25	6.12	5.69	110.29	6.52	490.54	10.11
0.5339	89.6494	83.70	4.08	3.56	107.96	4.32	297.82	18.08
0.1987	86.3243	80.29	1.52	1.21	101.68	1.61	97.17	27.55
0.5337	89.6484	83.69	4.07	3.56	107.96	4.32	297.69	18.09
0.4446	89.1074	82.81	3.40	2.90	106.65	3.60	240.38	20.64
0.5244	89.6037	83.60	4.00	3.49	107.83	4.25	291.58	18.35
0.5072	89.5134	83.43	3.87	3.36	107.60	4.11	280.32	18.85
0.0888	84.4678	79.11	0.68	0.51	98.81	0.72	40.12	30.54
0.4346	89.0314	82.71	3.32	2.83	106.49	3.52	234.15	20.93
0.0193	83.0987	78.34	0.14	0.08	96.78	0.16	6.22	32.15
0.1906	86.2013	80.20	1.46	1.16	101.49	1.54	92.85	27.77
0.4742	89.3149	83.11	3.62	3.12	107.12	3.84	259.11	19.80
0.9762	88.6456	87.76	7.39	7.12	110.50	7.90	625.06	5.01
0.4061	88.7969	82.43	3.11	2.63	106.01	3.29	216.53	21.74
0.7080	89.9861	85.35	5.39	4.90	109.74	5.73	418.05	13.01
0.2119	86.5216	80.42	1.62	1.30	102.00	1.72	104.30	27.18
0.5039	89.4949	83.40	3.85	3.34	107.55	4.08	278.16	18.95
0.2088	86.4760	80.39	1.60	1.28	101.93	1.69	102.63	27.27
0.8485	89.5649	86.64	6.44	6.04	110.43	6.87	523.21	8.84
0.5253	89.6077	83.61	4.01	3.49	107.85	4.25	292.12	18.33
0.9890	88.5257	87.87	7.48	7.23	110.47	8.00	635.56	4.62
0.6711	89.9940	85.01	5.11	4.61	109.45	5.43	391.62	14.09
0.2861	87.5310	81.20	2.19	1.79	103.68	2.32	145.61	25.12
0.3752	88.5139	82.12	2.87	2.41	105.46	3.04	197.77	22.62
0.2754	87.3956	81.09	2.11	1.72	103.45	2.23	139.51	25.42
0.1736	85.9338	80.02	1.33	1.05	101.06	1.41	83.77	28.24
0.7563	89.9111	85.80	5.75	5.28	110.05	6.12	453.37	11.58
0.2311	86.8001	80.63	1.77	1.42	102.46	1.87	114.83	26.65
0.1836	86.0913	80.12	1.41	1.11	101.31	1.49	89.07	27.96
0.0342	83.4050	78.51	0.26	0.17	97.23	0.28	13.35	31.92