KAUNAS UNIVERSITY OF TECHNOLOGY

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SMART SOLAR PHOTOVOLTAIC POWER SYSTEM CONTROL

Master's Degree Final Project

Supervisor

Assoc. prof. dr. Vaitkus Vygandas

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Final Degree Project (621H66001)

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SUMMARY

As the Maximum Power Point Tracking (MPPT) of a photovoltaic (PV) cell changes with respect to the atmospheric condition, it plays an important role in solar power generation system. A Smart Solar Panel System has been developed, consisting of the dual axis tracking unit which uses the time, date and geographical co-ordinates to find out the horizontal and azimuth angle of sun. This data is used to point the solar panel to orient itself for receiving maximum irradiance. These factors are also included for tracking maximum power. MPPT technique is dependent on V_{ph} and I_{ph}. MPPT is used in PV systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. This work introduces a panel tracker to get the maximum irradiance from the sun depending upon light condition. PV generators exhibit nonlinear I-V characteristics and Maximum Power Point that vary with solar isolation. An intermediate DC- DC converter can therefore increase efficiency by matching the PV system to the load and by operating the solar cell arrays at their Maximum Power Point. The Maximum Power Point tracking with DC-DC converter extracts the maximum power from the panel to the local storage.

In this work, Smart Solar Panel System is described which uses Maximum Power Point Tracking process, dP/dV feedback method algorithm using the measurement of Array voltage (V_{pv}) and Array current (I_{pv}) and is verified by simulating in Matlab Simulink.

SANTRAUKA

Fotoelektrinių elementų sistemos (PV) maksimalios galios taško sekimas (MPPT) priklausomai nuo besikeičiančių faktorių užima svarbų vaidmenį saulės elektros energijos gamybos sistemoje. Sumani saulės fotoelektrinių saulės elementų sistema buvo sukurta pasitelkiant dviejų ašių sekimo įrenginį, kuris naudoja laiką, datą ir geografines koordinates, kad nustatytų saulės padėtį. Šie duomenys naudojami pakreipti saulės elementų sistemą taip, kad ji būtų statmena krentantiems saulės spinduliams ir gautų maksimalų apšvietimą. Šie rodikliai taip pat naudojami maksimalios galios gaunamos iš sistemos užtikrinimui. MPPT sekimo algoritmas priklauso nuo V_{ph} ir I_{ph}. MPPT naudojamas fotoelektrinių saulės elementų sistemose, siekiant maksimizuoti sistemos išėjimo galią ir jos stabilumą, nepriklausomai nuo temperatūros ir apšvietimo sąlygų bei apkrovos elektrinių charakteristikų kitimo. Fotoelektriniai elementai turi netiesinę I-V charakteristiką, todėl maksimalus galios taškas nuolat keičia poziciją priklausomai nuo kintančių išorės sąlygų. Po atliktų tyrimų galima teigti, kad maksimalios galios taško sekimas leidžia užtikrinti maksimalų galios kiekį gaunamą iš fotoelektrinės sistemos ir jos pertekliaus kaupimą baterijoje.

Šiame darbe pateikiama ir MATLAB/Simulink programinės įrangos aplinkoje tiriama fotoelektrinių elementų sistema ir jos valdymas naudojant maksimalios galios taško sekimo algoritmą pagrįstą dP/dV sekimų.

Acknowledgements

I would like to place on record my deep sense of gratitude to Assoc.Prof.dr.Vaitkus Vygandas Dept. of Automation, KTU for his generous guidance, help and useful suggestions. Without his guidance, this work would not have been possible. I am extremely thankful to Prof.dr. Gintaras Dervinis, Head of the department of Automation, KTU for providing me useful suggestions throughout the course of the work. I express my sincere gratitude to Prof.dr.Alma Dervinis Vice dean of Faculty of Electrical and Electronics Engineering, KTU for her guidance, help and useful suggestions.

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CONTENTS

1. INTRODUCTION

People are much concerned with the petroleum fuel exhaustion and environmental problems caused by the conventional power generation, hydro, tidal energy sources among which photovoltaic panels and wind-generators are now widely used. Photovoltaic sources are used Today photovoltaic sources are used in many applications. A powerful attraction of PV systems is that electric power is produced without harming the environment, by directly transferring the power to the load or to the grid. Now the main application of solar energy is battery charging, water pumping, home power supply, swimming-pool heating systems, satellite power systems, grid transmission etc. They have the advantage of being low cost maintenance and pollution-free but their installation cost is high and, in most applications they require a power conditioner (DC/ DC converter) for load interface. Since PV modules still have relatively low conversion efficiency, the overall system cost can be reduced using high efficiency power conditioners which, in addition, are designed to extract the maximum possible power from the PV module.

The Sun is moving in the direction from east to west. This is due to the apparent motion of the Sun caused by the rotation of earth on its axis. Because of this movement we cannot get maximum irradiance in solar module throughout the day. When the Sun's rays are perpendicular to the absorbing surface, the power density on the surface is equal to the incident power density**.** PV systems convert energy of sun directly into electricity by making use of the photovoltaic effect. The dual axis tracking unit process uses the time, date and geographical co-ordinates to find out the horizontal and azimuth angle of sun. This data (Θ, ϕ) is used to point the solar panel angle is changed by axis tracking unit to receiving maximum irradiance. MPPT technique is dependent on Vph and Iph. MPPT is used in PV systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. With connected cells and a tough front glass, a protective back surface and a frame, the module can be used for real-world systems.

Module is a group of PV cells connected in series and/or parallel and encapsulated in an environmentally protective laminate. The PV module is the smallest package that produces useful power. The process involved in manufacturing these modules requires high precision and quality control in order to produce a reliable product. A group of panels that comprises the complete PV generating unit is called PV array.

A very common and simple MPPT technique is to compare the PV array power with a constant reference voltage and current which corresponds to the PV power at the maximum power point, under specific atmospheric conditions. The resulting difference signal (PWM signal) is used to drive a power conditioner which interfaces the PV array to the load. Although the implementation of this method is simple, the method itself is not very accurate, since it does not take into account the effects of temperature and irradiation variations.

In the PV smart solar panel system with tracking sun irradiance of solar panel shown in Fig.1.1, the PV array output voltage and current calculated given to MPPT controller, which compares the PV output power before and after a change in the duty cycle of the dc/dc converter control signal. The power is stored in bank of battery and connecting to load with a step up of voltage. The system is modelled and controlled using Matlab Simulink and Matlab.

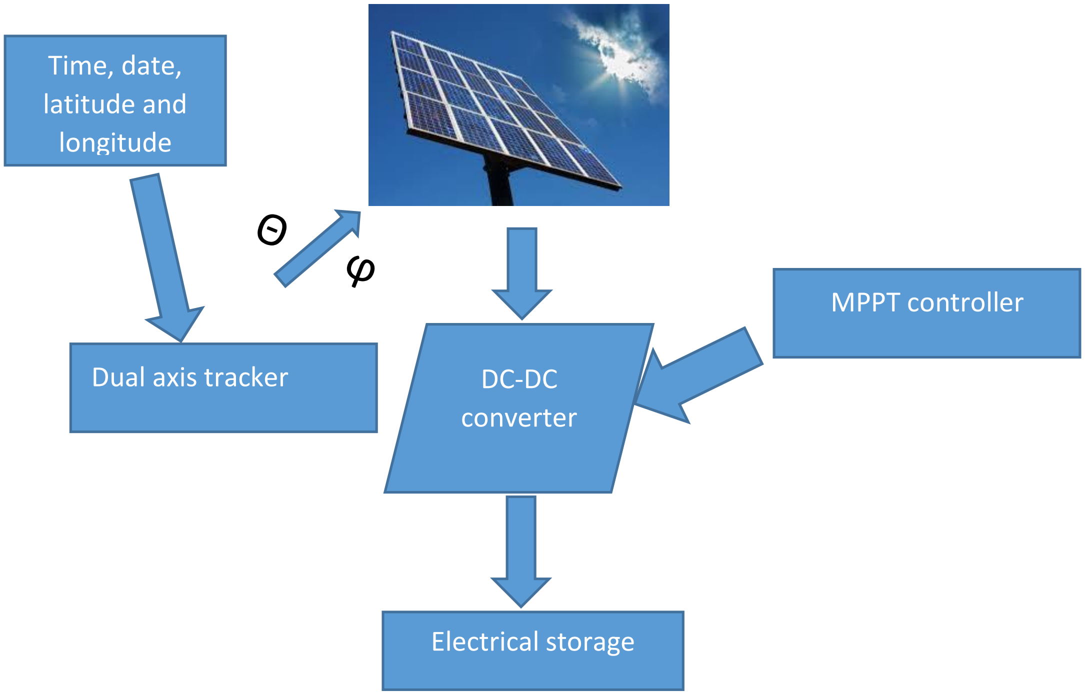

Fig1.1 Flow chart of the workflow

1.1 About Solar Panel Tracking

Solar panel tracking helps in moving the solar panels according to the movement of the sun and Maximum power point tracking is used to achieve maximum power from the PV module.

1.2 Existing Problem

- Due to increase in global warming, usage of renewable energy is very essential.
- Solar cells have been hooked with fixed elevating angles. They do not track the sun and therefore, the efficiency of power generation is low.
- Available sunlight is randomly dependant on environmental conditions like temperature and irradiance. This may reduce efficiency of power generation from PV panel

1.3 Aim of The Work

My goal is to create smart solar Photovoltaic Power System control algorithm and evaluate its efficiency.

1.4 Tasks of The Work

- Create Photovoltaic system model
- Implement in MATLAB
- Create MPPT algorithm
- Experimental investigation

2. LITERATURE REVIEW

This part of research provides analysis of the existing literature to present the importance of solar tracking system that is used to generate more efficient power from the solar energy. Solar tracking system is used to generate more energy from the Sun. This part of the research provides theoretical algorithms to convert energy from sunlight to usable energy by using solar tracking system.

2.1 Solar Energy

Solar energy is the most powerful resource that can be used to generate power. So far the efficiency of generating power from solar energy is relatively high. Thus, increasing the efficiency of generating power of solar energy is very important [1].

Recent developments in solar energy focus on maximizing system efficiency [2]. This solar energy is a renewable form of energy. The earth surface receives solar energy basically depends on several factors such as the time of the day and the atmospheric conditions. The solar energy was used to generate electricity. It is estimated that solar energy will become the largest source of electricity by the year 2050[3]. For this reason, there should be a larger investment in harnessing solar energy [4] The main purpose of this research is to efficiently harness solar energy and convert the energy in a useful form for common domestic appliances and devices. The system responds to its environment in the shortest possible amount of time since it is designed as a real-time system.

The increasing energy demand, continuous drawback of the existing sources of fossil fuels and increasing concern about environmental pollution pushed researchers to explore new technologies for the production of electricity from clean sources, renewable such as solar, wind etc. Solar energy is the oldest primary source of energy. It is a source of clean, renewable energy and it is found in abundance in every part of the world. Using solar energy, it possible to convert into mechanical energy or electricity with adequate efficiency [5].

Solar energy, which comes from the sun in the form of solar irradiance, can be directly converted to electricity by using photovoltaic(PV) technology. There are numerous studies about photovoltaic performance. Although the efficiency of the PV system has increased through many improvements such as tracking, to generate maximum energy.

2.2 Solar Tracking System

A device called solar tracker, that orients payload towards the Sun. Payloads are usually solar panels, parabolic troughs, reflectors, mirrors and lenses. Solar tracking is used to improve the efficiency [2]. Global warming has increased the demand and request for green energy produced by renewable sources such as solar power. Consequently, solar tracking is increasingly being applied as a sustainable power generating solution.

Solar Tracking System is a device for orienting a solar panel or concentrating a solar reflector or lens towards the sun. Precise tracking of the sun is achieved through systems with single or dual axis tracking. Installation size, local weather, degree of latitude and electrical requirements are all important considerations that can influence the type of solar tracker best suited for a specific solar installation. [6].

To get a larger amount of solar energy the efficiency of photovoltaic systems has been studied by a large number of scientists. In general, there are three ways to increase the efficiency of photovoltaic systems. The first method is to increase the efficiency of power generation of the solar cells, the second is related to the efficiency of the control algorithms for the energy conversion, and the third approach is to adopt a tracking system to achieve maximum solar energy [5].

2.3 Theoretical Aspects of MPPT Algorithms

2.3.1 Perturb and Observe Algorithm

The P&O algorithm is also called 'hill climbing', while both names refer to the same algorithm depending on how it is implemented. Hill-climbing consist of a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter. In the case of the Hill climbing, perturb the duty cycle(D) of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both name refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. On the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power [2].

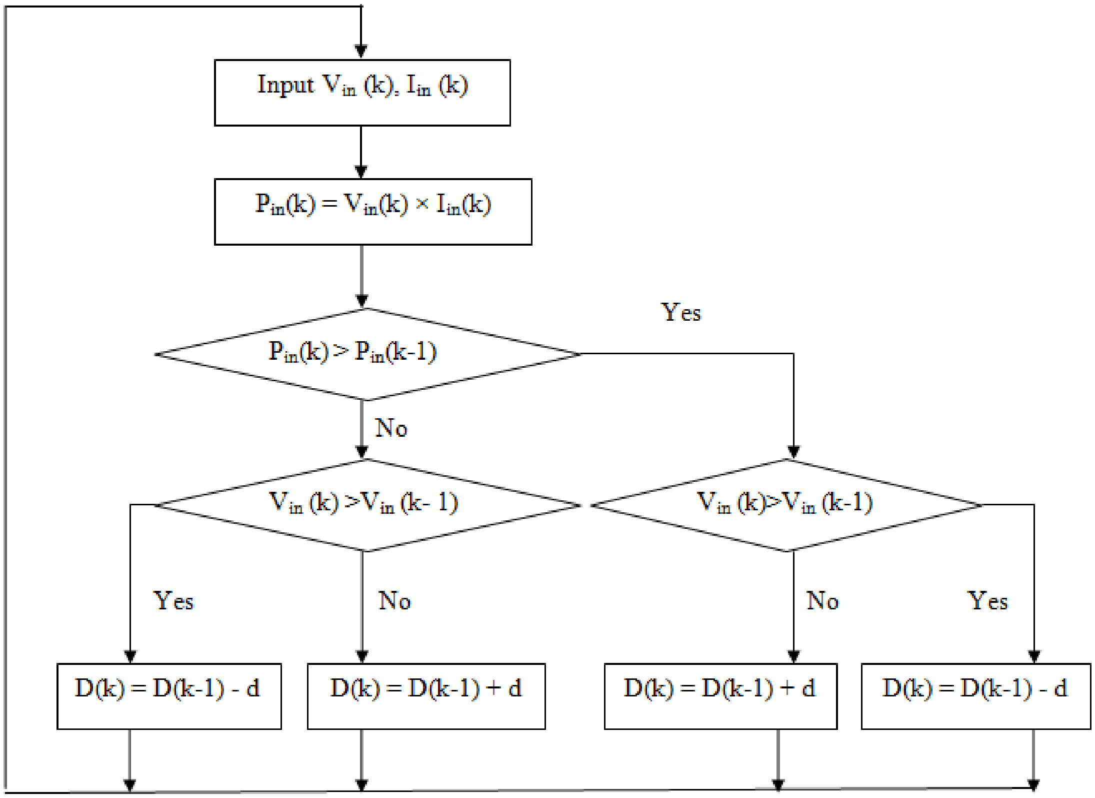

Fig. 2.1: Flowchart of P&O Algorithm

The P&O algorithm, operates by increasing or decreasing the array terminal voltage, or current, at regular intervals and then comparing the PV output power with that of the previous sample point. If the PV array operating voltage changes and power increases the control system, adjusts the PV array operating point in that direction; otherwise the operating point is moved in the opposite direction. At each perturbation point, the algorithm continues to operate in the same manner. The process is repeated until MPP is reached output.Fig.2.1 shows the block diagram for P&O MPPT algorithm [7].

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

Table 2.1: Operation of P&O Algorithm

Drawbacks of P&O Algorithm

- The P&O causes operating point to oscillate around MPP.
- Occasional deviations from the maximum operating point in the case rapidly changing atmospheric conditions such as broken clouds.
- Predicting correct perturbation size is important in providing good performance in both dynamic and steady-state response.
- The classic P&O method has the disadvantage of poor efficiency at low irradiation.

2.3.2 Incremental Conductance Method

Incremental Conductance method proposed to overcome the disadvantages of P&O method. Avoiding the P&O algorithm drawbacks formed the basis of the IC algorithm in which the array terminal voltage is always adjusted according to its value relative to the MPP voltage. The incremental conductance method employs the slope of PV array-power characteristics to track MPP. The basic idea is that at the MPP the derivative of the power with respect to the voltage vanishes because the MPP is the maximum of the power curve. To the left of the MPP the power is increasing with the voltage, i.e. slope of the PV curve is positive, and it is decreasing to the right of the MPP, i.e. slope of the PV curve is negative [8]. The algorithm can be represented by a flowchart as shown in fig.2.2. Flowchart of Incremental Conductance Method [9].

$$\frac{dI}{dV} = -\frac{I}{V}, at\ MPP$$

$$\frac{dI}{dV} > -\frac{I}{V}, \qquad to\ the\ left\ of\ \ MPP$$

$$\frac{dI}{dV} < -\frac{I}{V}, \qquad to\ the\ right\ of\ \ MPP$$

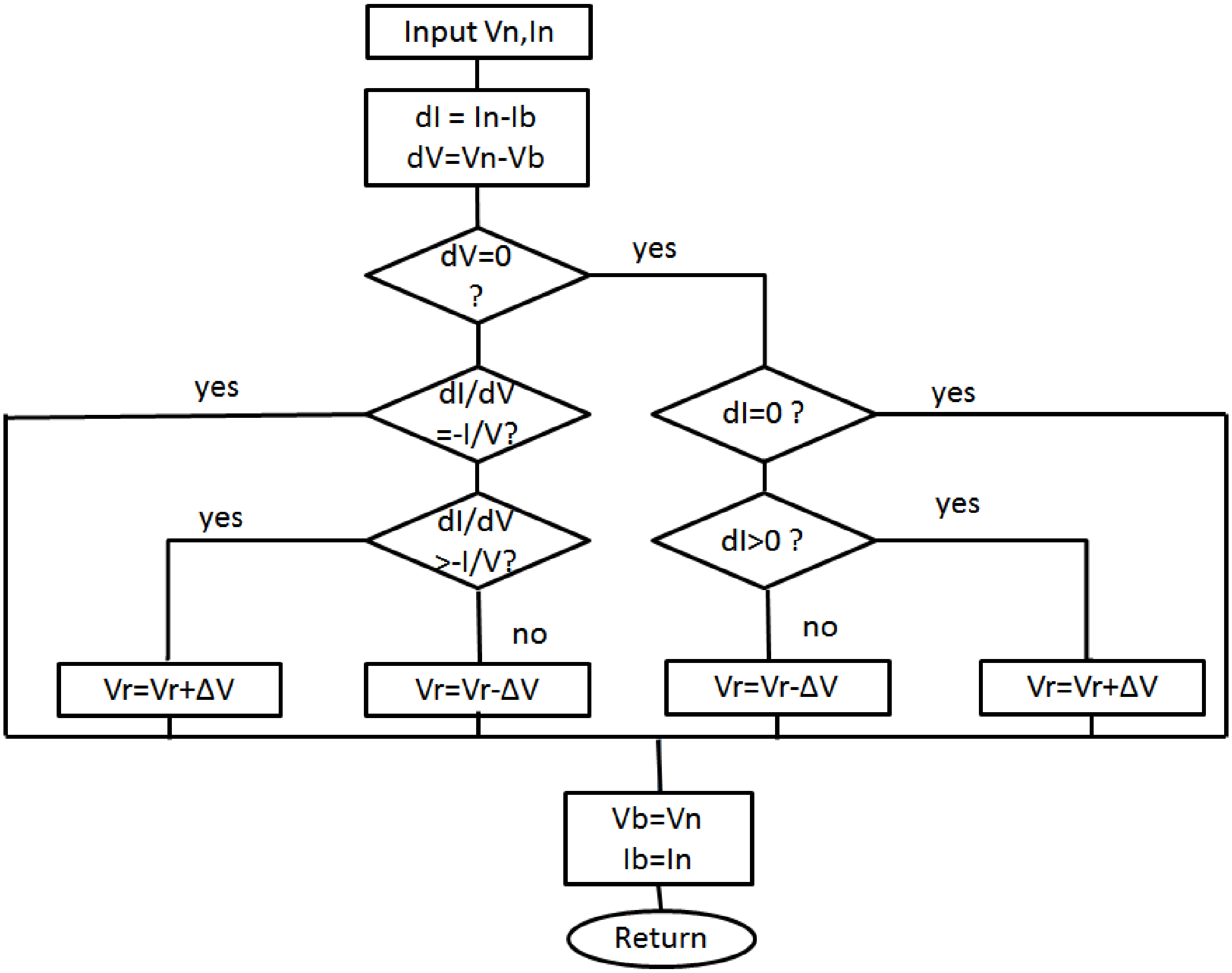

Fig. 2.2: Flowchart of Incremental Conductance Method

Drawbacks of IC Method

- Complex Control Circuitry
- Fail to track optimum power under partial shading conditions

2.3.3 OC Voltage Method

This method uses approximately linear relationship between open circuit voltage and maximum power point voltage under different environmental conditions.

$$V_{MPP} = KV_{OC} \text{ -----------(2.1)}$$

where, K is a constant, which depends on the solar cell characteristics. This constant is empirically derived based on measurement of the V_{oc} and V_{mpp} under different environmental conditions. It is difficult to choose an optimal value for the constant K, however values for this parameter ranging from 0.73 to 0.80 have been reported in polycrystalline PV modules. The PV system is open circuited at the load end for a second to measure V_{oc}. The power converter has to be shut down momentarily due to which loss of power occurs in each measurement. From eqn. (2.2) V_{mpp} is determined following each measurement of the V_{oc}. In each successive stage as MPP is tracked this value of V_{mpp} which is chosen as the set point is assumed to remain relatively constant over a wide range of temperature and irradiance values. Figure 2.3 shows the flowchart of OCV method [10].

$$I + V\frac{dI}{dt} = 0 \text{---------------}(2.2)$$

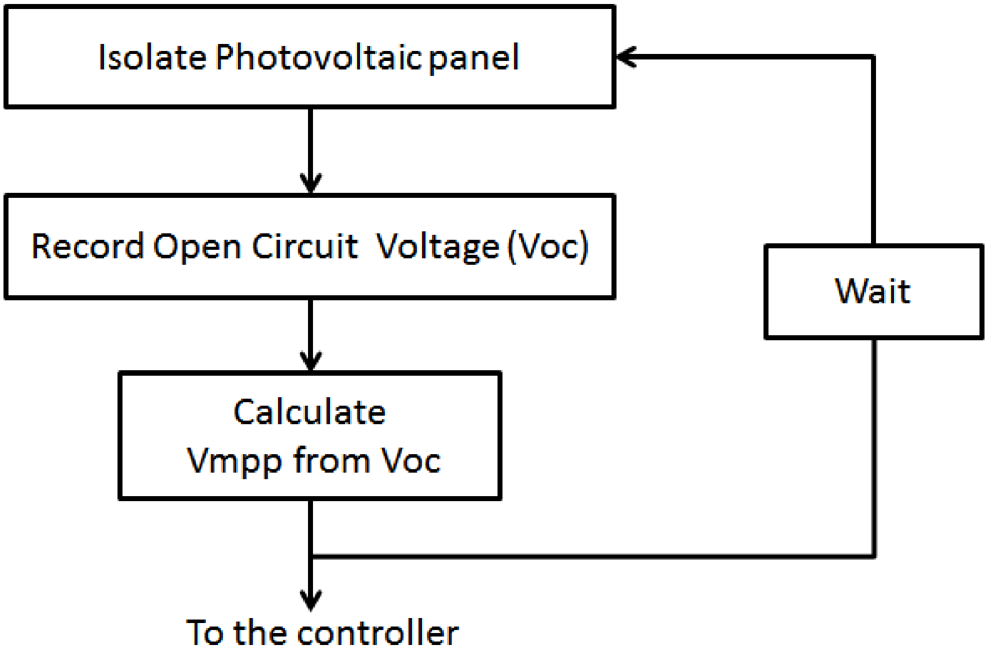

Fig 2.3 flowchart of OCV method

Advantage of OCV method

- This method has advantages including relative ease of implementation and low cost.

Drawbacks of OCV Method

- The measurement of V_{oc} requires periodic shedding of the load, which may interfere with circuit operation and will cause more power losses.

- Value of K is no more valid in the presence of partial shading of PV array this leads to implantation complexity and incurs more power loss.

2.3.4 SC Current Method

This method is similar to OC voltage method. There is also an approximately linear relationship between the short circuit current(I_{SC}) of the solar panel and the MPP current(I_{mpp}), which can be described by the following equation:

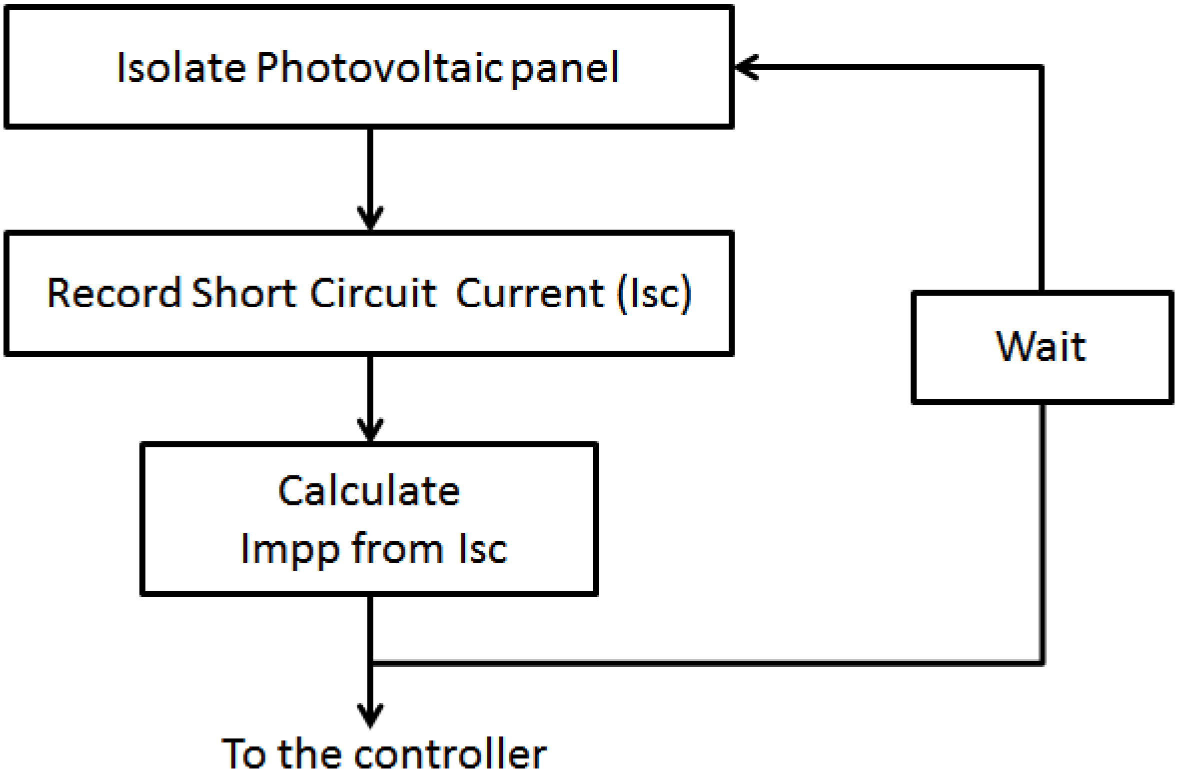

Fig2.4 flowchart of SCC method

$$Impp = KIsc \text{------------}(2.3)$$

where, K is a constant between 0.8 and 0.9 and can be calculated by analysing the PV system at a wide range of solar radiations and temperature. Similar to the OCV method, the load should be shed in order to determine the I_{SC}. A solution to this problem is to use pilot cells. But this can add to the system cost which is not much recommended. Due to practical issues associated with measuring the I_{SC}, its implementation costs are higher. The flowchart of SCC method is as shown in fig.2.4 [11].

Drawbacks of SCC Method

- Measuring the I_{SC} during the operation is Problematic.
- Cost of the system further increases due to the addition Switch has to be added to the power converter circuit to periodically short the PV array So that I_{SC} can be measured using the current sensor.
- Power output is reduced when finding I_{SC} and also causes the MPP never perfectly matched.

2.3.5 Fuzzy Logic MPPT Controller

The voltage and current of the PV panel are measured instantly. Then, the power is calculated and saved in a vector. The input variables of the Fuzzy logic controller are created based on the eqns. (2.4) and (2.5). The algorithm steps are shown in the flowchart shown in fig.2.5. [12]

$$e(t) = \frac{\Delta P}{\Delta V} = \frac{P(t)-P(t-1)}{V(t)-V(t-1)} \text{-----------} (2.4)$$

$$\Delta e(t) = e(t) - e(t-1) \text{------------} (2.5)$$

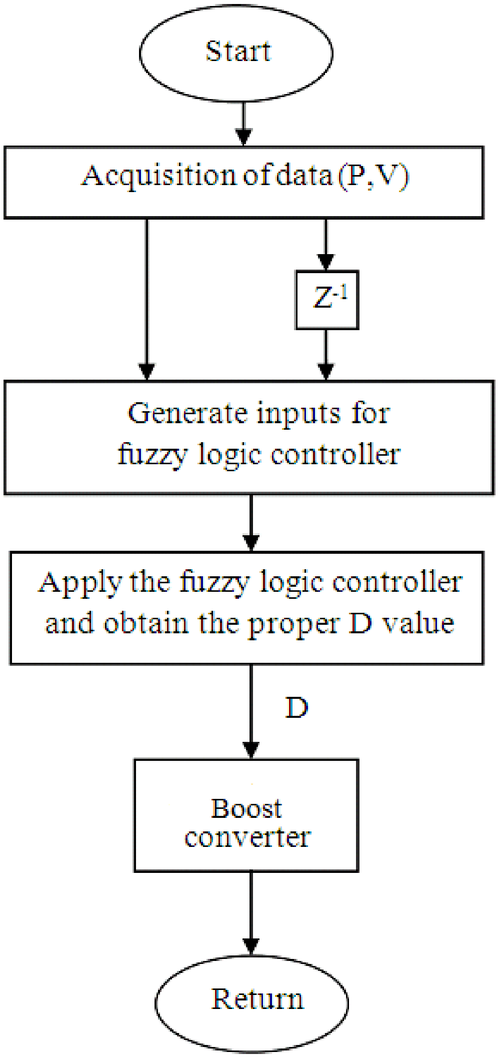

Fig2.6 Flowchart of FLC Based MPPT

The main parts of FLC, fuzzification, rule-base, inference and defuzzification, are shown in fig. 2.6 The input defined in eqns. (2.4) and (2.5) need to be fuzzified by some membership functions. For each input value, the respective membership function returns a value of m. The max-min method was applied to extract the m from the triangle type membership function. Then a rule base must be applied to the obtained membership function according to Mamdani or Sugeno's method. In Defuzzification, the centroid method is applied to return a proper value. for the duty cycle variation (ΔD). The defuzzified output value of the FLC must be added to a reference value of duty cycle which is considered equal to 0.5 for the current study. The result is the optimum value of D that has to be sent to the boost converter as a control signal [12].

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2.3.6 Neural network MPPT

In order to accurately identify the MPP using ANN the Wi has to be determined appropriately based on the relationship between the input and the output of the PV system. Therefore, the PV array is tested over months or years and the pattern between the input and output of the neural network are recorded. The input signal to each neuron is either the signal received from neighbouring neurons or the ANN input variables associated from the non-linear system under study. In application of ANN for MPPT, the input variables can be PV array parameters like V_{OC} and I_{SC}, atmospheric data like irradiance and temperature, or any combination of these. The output of ANN is usually one of several reference signals, the most common of which is the duty cycle signal used to drive the power converter to operate at or close to the MPP [13].

Since most PV arrays exhibit different output characteristics, an ANN has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array are also time-varying, which implies that the neural network has to be periodically trained to guarantee accurate tracking of MPP. In order to implement periodical training, new data has to be collected, which is a time consuming process. [13]

2.3.7 Comparison of Different MPPT Methods

The comparative study of different MPPT algorithms are carried out and the analyses are summarised in table 2.2

Algorithm	**Complexity**	**Convergence Speed**	**Sensed Parameters**	**Prior Training**	**Efficiency**
P&O	Low	Low	V and I	No	Low
IC	Medium	Low	V and I	No	High
OCV	Low	Medium	V	Yes	Low
SCC	Medium	Medium	I	Yes	Low
FLC	High	Fast	Depends	Yes	High
ANN	High	Fast	Depends	Yes	High

Table 2.2: Comparison of Different MPPT Algorithms

3. SOLAR ENERGY

Several factors are affecting solar radiation, mainly atmospheric effect including absorption and scattering, local variation in the atmosphere such as water vapour, clouds and pollution, latitude of the location and the season of the year and time of day. Due to the movement of earth about its axis, there will be changes in the angle at which the direct light will strike the earth. And the intensity of the sunlight is also dependent upon the location of a point on earth, time of day and month. So we can track the maximum irradiance from sun when the panel and sun are exactly parallel. The parameters used for tracking are Time difference from Greenwich Mean Time (GMT) in hours, number days since the start of the year (date), longitude, latitude and local time in 24-hour format. This paper discusses about how to calculate these values, making a matlab model and showing the difference between the power with and without the panel being tracked.

Twelve noon local solar time (LST) is defined as when the sun is at the pinnacle. Local time (LT) usually varies from LST because of the eccentricity of the Earth's orbit, The Local Standard Time Meridian (LSTM) is a reference meridian used for a particular time zone and is similar to the Prime Meridian, which is used for Greenwich Mean Time [16].

$$LSTM = 15°. \Delta\text{TGMT}\text{-------------(3.1)}$$

Where ΔTGMT is the difference of the Local Time (LT) from Greenwich Mean Time(GMT) in hours.15 degrees is obtained using 360/24hours.

The equation of time (EoT) (in minutes) is an empirical equation that corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt [16].

$$EoT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B) \quad \text{-----(3.2)}$$

where

$$B = \frac{360}{3}\,65(d - 81)\text{----------------------------(3.3)}$$

d is the number of days since the start of the year.

The net time correction factor (in minutes) accounts for the variation of the Local Solar Time (LST) within a given time zone due to the longitude variations within the time zone and also incorporates the EoT above.

$$TC = 4(Longitude - LSTM) + EoT \text{ ------------------(3.4)}$$

The factor of 4 minutes comes from the fact that the Earth rotates 1° every 4 minutes.

The Local Solar Time (LST) can be found by using the previous two corrections to adjust the local time (LT).

$$LST = LT + \frac{TC}{60} \text{ -----------------------(3.5)}$$

The Hour Angle converts the local solar time (LST) into the number of degrees which the sun moves across the sky. By definition, the Hour Angle is 0° at solar noon. Since the Earth rotates 15° per hour, each hour away from solar noon corresponds to an angular motion of the sun in the sky of 15°. In the morning the hour angle is negative, in the afternoon the hour angle is positive [16].

$$HRA = 15°(LST - 12) \text{ --------------(3.5)}$$

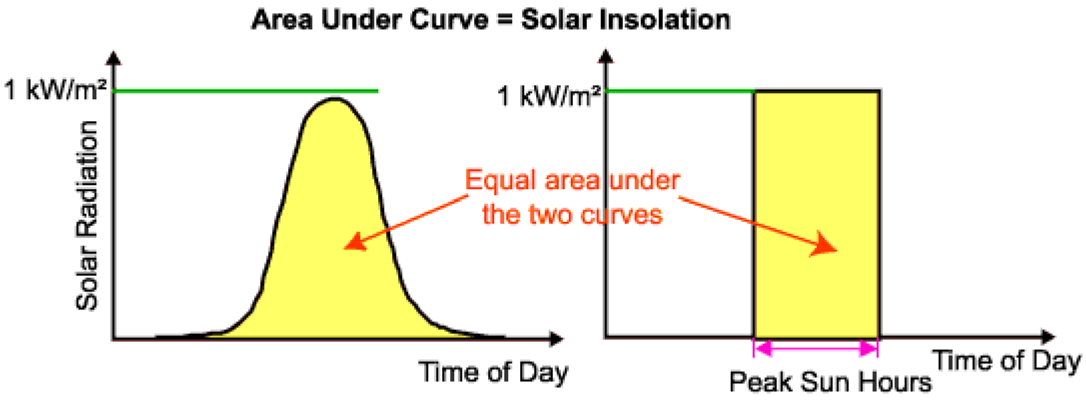


Fig 2.1 Average solar radiation in one day

4. MEASUREMENT OF SOLAR RADIATION

To design a solar panel system, it is essential to know about the amount of solar energy available. Solar energy in a panel is dependent upon different factors like Total solar panel area, Efficiency factor of module, Annual average solar radiation on tilted panels, Performance ratio, coefficient for losses and also shadow effect and clement changes. Solar irradiance is usually measured in unit of kW/m^2. Normally 0 to 1 kW/m^2 irradiance is available from day till night. The local weather is also an important factor to affect the solar irradiance. In summer we can get the maximum irradiance and the maximum power. Figure 3.1 shows the Annual average solar radiation $\frac{kW}{m^2}/a$. During the winter time 50% of available energy is using for heating so it is essential to catch the maximum power from the available sources. From figure 3.1[10] we can see that the available annual average solar radiation northern Europe is less than 1200 $\frac{kW}{m^2}/a$ and the southern Europe is 1200-1800 $\frac{kW}{m^2}/a$.

To calculate the annual energy output of a photovoltaic system

$$\boldsymbol{E = A * r * H * PR}$$

E= Energy (kWh)
A = Total solar panel area (m²)
r = Efficiency factor of module (%)
H = Annual average solar radiation on tilted panel $\frac{kW}{m^2}/a$ (shadings not included)
PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

Efficiency factor of module is the energy conversion efficiency (r) of a solar cell is the percentage of the solar energy to which the cell is exposed that is converted into electrical energy. Power (in kWp) of one solar panel divided by the area of one panel. For example, the solar panel yield of a PV module of 1 kWp with an area of 6.4 m² is 15.6% A (m²/1kWp) * r (%) = 1 kWp.

The performance ratio is a measure of the quality of a PV plant that is independent of location and it therefore often described as a quality factor. The performance ratio (PR) is stated as percent and describes the relationship between the actual and theoretical energy outputs of the PV plant. It thus shows the proportion of the energy that is actually available for export to the grid after deduction of energy loss (e.g. due to thermal losses and conduction losses) and of energy consumption for operation.

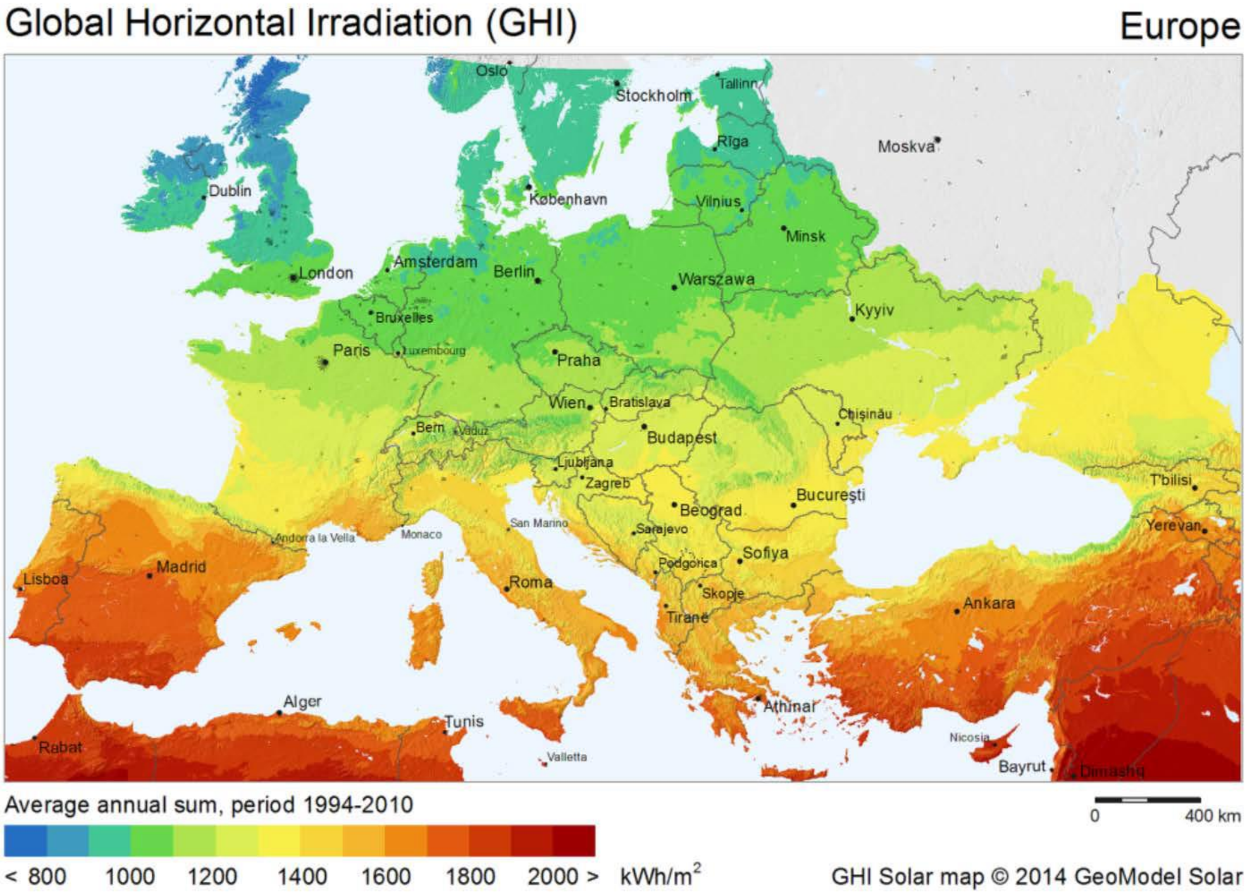


Fig 4.1: Annual average solar radiation

The closer the PR value determined for a PV plant approaches 100 %, the more efficiently the respective PV plant is operating. In real life, a value of 100 % cannot be achieved, as unavoidable losses always arise with the operation of the PV plant (e.g. thermal loss due to heating of the PV modules). High-performance PV plants can however reach a performance ratio of up to 80 %) [17]

For measuring global irradiance using a Pyrhelometer and there is another method for measuring solar radiation, which is less accurate but less accurate but less expensive using sunshine recorder.

5. ANGLES AND FACTORS AFFECTED BY SOLAR IRRADINCE

The Solar irradiance in the earth surface is different in different places. Solar irradiance is the power density incident on an object due to illumination from sun. However, the distance from the sun increases the total power spread-out over much larger surface area. So the solar irradiance in the solar panel decreases when the distance from Sun to earth increases. This is happening because of rotation of earth around the sun and its own axis. So in this work, the co-ordinates of a place are given as input in Matlab Simulink and maximum power is obtained using Tracking of the Solar panel. For locating the place, input co-ordinates are given in Matlab Simulink. The five input parameters are: Time difference from Greenwich mean time(GMT), number of days from starting of the year (Let's say January 1 is one and February 1 is 32), Longitude, Latitude and Local time in 24-hour clock format.

The four main factors affecting the solar irradiance are mainly:

- Atmospheric effect mainly absorption and scattering.
- Variation in the atmosphere such as water vapour, clouds and pollution.
- Latitude and longitude of the location.
- Season of the year and the time of the day.

5.1 Air Mass Number

Air mass number is a factor to be considered while calculating intensity of light. When the light travels through the air, there will be reduction in the intensity of the light due to particles such as dust and air and this quantity is called as Air Mass Number (AM). Here earth is not considered as flat horizontal layer because air mass number is dependent on zenith angle. Zenith angle will change because of curvature of earth. At noon air mass number is almost equal to 1.

$$AM = \frac{1}{\cos(\theta)+0.50572*(96.07995-\theta)^{-1.6364}} \text{-------------------(5.1)}$$

A reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere and a change in the spectral content of the solar radiation due to the greater absorption or scattering of some wave length [14]. Local variation in the atmosphere such as water vapour, cloud and pollution, which have additional effect on the incident power spectrum and directionally.

5.2 Declination Angle(δ)

The declination angle, denoted by δ, varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. If the Earth were not tilted on its axis of rotation, the declination would always be 0°. However, the Earth is tilted by 23.45° and the declination angle varies plus or minus this amount. Only at the spring and fall equinoxes is the declination angle equal to 0°. [15]

The declination angle can be calculated by the equation.

$$\delta = \sin^{-1}(\sin(23.45°)\sin(\frac{360}{365})(d-81)) \text{------------------(5.2)}$$

where d is the day of the year with Jan 1 as d = 1.

The declination is zero at the equinoxes (March 22 and September 22), positive during the northern hemisphere summer and negative during the northern hemisphere winter. The declination reaches a maximum of 23.45° on June 22 and a minimum of -23.45° on December 22. [7]

5.3 Elevation angle(α)

The elevation angle is the angular height of the sun in the sky measured from the horizontal. Confusingly, both altitude and elevation are also used to describe the height in meters above sea level. The elevation is 0° at sunrise and 90° when the sun is directly overhead. The elevation angle varies throughout the day. It also depends on the latitude of a particular location and the day of the year.

For Northern Hemisphere

$$\alpha = 90 - \varphi + \delta$$

φ is the latitude of the location of interest δ is the declination angle, which depends on the day of the year

for the Southern Hemisphere

$$\alpha = 90 + \varphi - \delta$$

while the maximum elevation angle is used even in very simple PV system design, more accurate PV system simulation requires the knowledge of how the elevation angle varies throughout the day.

$\alpha = \sin^{-1}(\sin\delta\sin\varphi + \cos\delta\cos\varphi\cos HRA)$------------------(5.3)

HRA is hour angle

5.4 Zenith angle(ζ)

As shown in Figure 4.1, the angle between the sun and the vertical. [16] The zenith angle is similar to the elevation angle, but it is measured from the vertical rather than from the horizontal, thus making the zenith angle = 90° - elevation.

$$\zeta = 90^{\circ} - \alpha$$

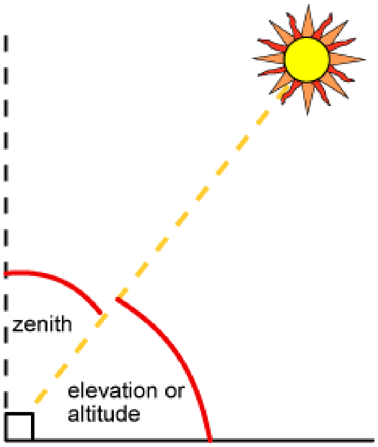


Figure 5.1 zenith and elevation

5.5 Azimuth angle

Azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere. The azimuth angle varies throughout the day as shown in the animation below. At the equinoxes, the sun rises directly from the east and sets directly west regardless of the latitude, thus making the azimuth angles 90° at sunrise and 270° at sunset. In general, however, the azimuth angle varies with the latitude and time of year and the full equations to calculate the sun's position throughout the day. Fig 4.2 shows the azimuth angle [16].

$$Azimuth = \cos^{-1}\left(\frac{\sin\delta\cos\theta - \cos\delta\sin\theta\cos HRA}{\cos\alpha}\right) \text{----------(5.4)}$$

HRA is the hour angle

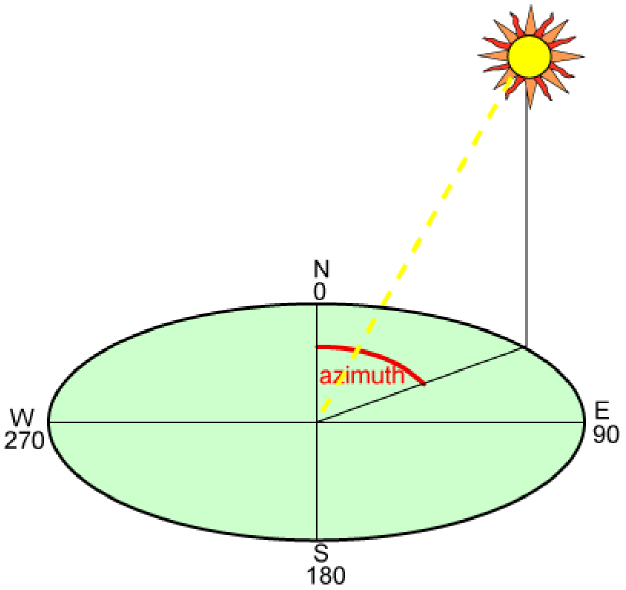
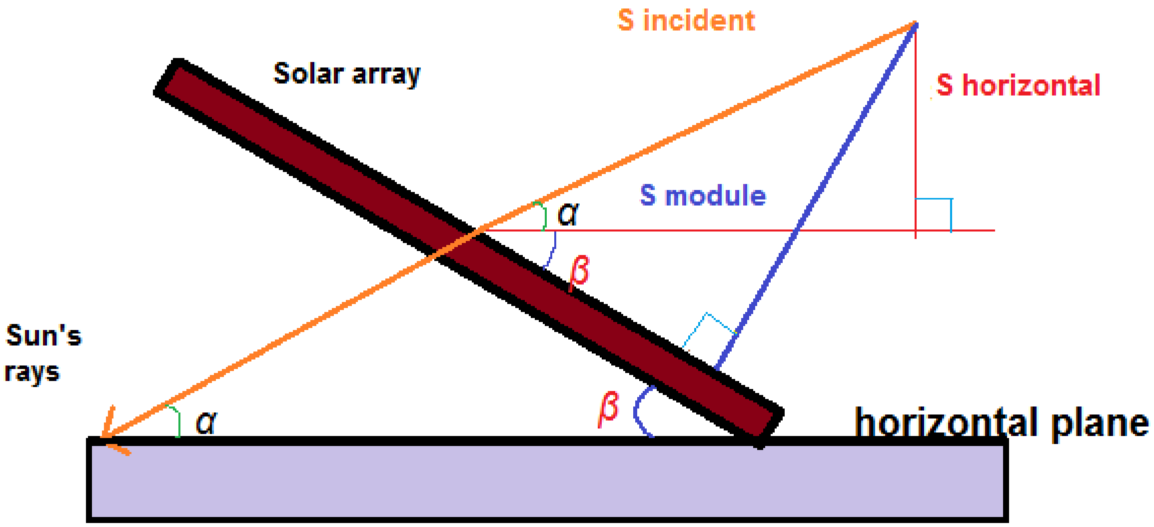


Figure 5.2 Azimuth angle

6. MODULE IRRADIANCE

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight. The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface. The following figure shows how to calculate the radiation incident on a tilted surface (S_{module}) given either the solar radiation measured on horizontal surface (S_{horiz}) or the solar radiation measured perpendicular to the sun ($S_{incident}$)[16].



$$S_{incident} = 1.353 * 0.7^{AM^{678}} \text{----------------(6.1)}$$

AM = Air mass number

$$Smodule = Sincident * (\cos\alpha \sin\beta \cos\Psi - \Theta + \sin\alpha \cos\beta) \text{--------------(6.2)}$$

Θ = Sun azimuth angle

Ψ= that Azimuth angle the module faces

α = Sun elevation angle

β = Module tilt angle

A module in the southern hemisphere will be facing north with $\Psi = 0°$ and a module in the northern hemisphere will typically face directly south with $\Psi = 180°$. S_{module} and $S_{incident}$ are respectively the light intensities on the module and of the incoming light in W/m², the $S_{incident}$ being a direct only component.

A module that directly faces the sun so that the incoming rays are perpendicular to the module surface has the module tilt equal to the sun's zenith angle ($90 - \alpha = \beta$), and the module azimuth angle equal to the sun's azimuth angle ($\Psi = \Theta$) [16].

In this research for the tracking of solar panel we have to make module tilt equal to the sun’s zenith angle, and module azimuth angle equal to the sun’s azimuth angle. In case the tracker is not used the module tilt and module azimuth is set as a constant value.

7. SOLAR MODULE REPESENTATION

Typically, a solar cell can be modelled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistances. Series resistance is due to hindrance in the path of own of electrons from *n* to *p* junction and parallel resistance is due to the leakage current. Modelling of PV cell involves the estimation of the I-V and P-V characteristics curves to emulate the real cell under various environmental conditions. An ideal solar cell is modelled by a current source in parallel with a diode. However, no solar cell is ideal and thereby shunt and series resistances are added to the model as shown in the fig.7.1[18, 19].

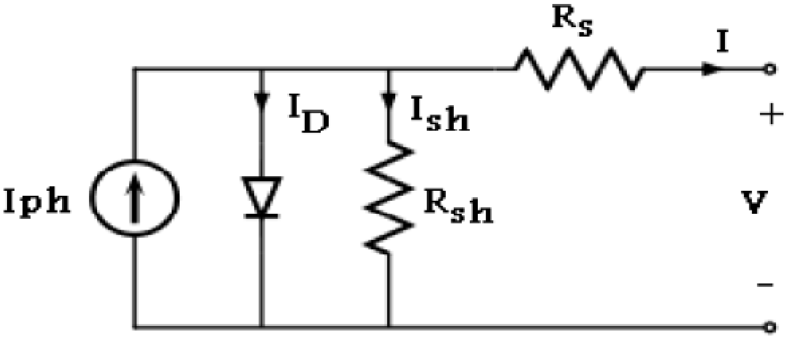


Fig. 7.1: Equivalent Circuit of a Solar Cell

Solar power is the conversion of electromagnetic radiation of solar energy to electrical energy. Since a typical PV cell produces less than 2W at 0.5V approximately, using the series and parallel connection of a solar module cell we can obtain the high power. [20] The equivalent circuit for the solar module arranged in NP parallel and NS series is shown in Fig. 7.2.

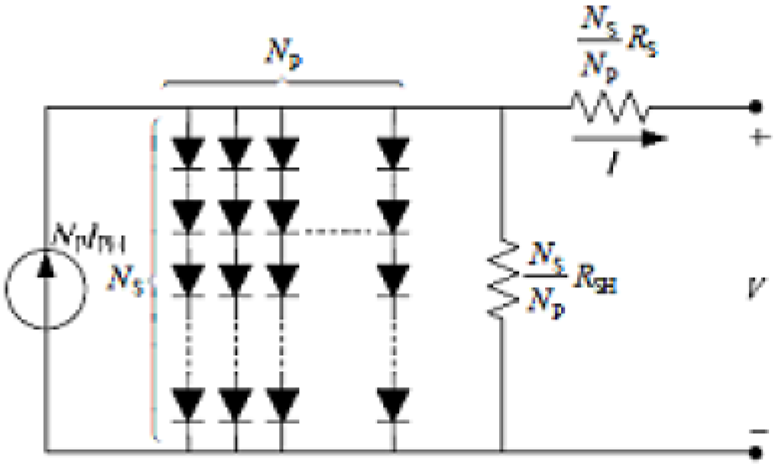


Fig. 7.2 Equivalent circuit model of generalized PV

Table 7.1 shows the constant values which is used in maltab simulink to generate PV current. [20]

Parameters	**Value**
Number of parallel solar module arranged (Ns)	100
Number of parallel solar module arranged (Np)	1
Cell's working temperature(T_c)	298 K
Short-circuit current temperature coefficient(K1)	0.0017
Series resistance (R_S)	0.22 kilo ohm
Bang energy of the semiconductor(E_G)	1.1
The ideal factor dependent on PV technology(A)	1.5
Reference temperature(Tref)	25°C
Reference short circuit current (I_{sc})	135A
Boltzmann's constant(K)	1.38*10^23J/K

Table 7.1 Constant Values

Equation for Photocurrent

$\text{Iph} = [\text{Isc} + \text{K1}(\text{Tc} - \text{T}ref)]\,\lambda$ -----------------(7.2)

I_{sc} = Short-circuit current

K_1 = Short-circuit current temperature coefficient

T_{ref} = Reference temperature

λ = solar insolation in kW/m^2.

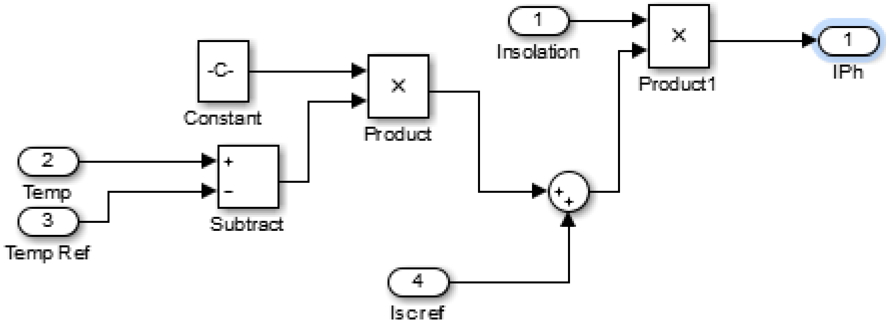


Figure 7.4 Photon current Matlab Simulation

The terminal current and voltage equation are follows:

$$I = \text{NpIph} - \text{NpIs}\left\{ e^{\frac{\frac{q\left(\frac{V}{\text{Ns}}+\text{IRs}\right)}{\text{Np}}}{\text{KTcA}}} - 1 \right\} - \frac{\frac{\text{NpV}}{\text{Ns}}+\text{IRs}}{\text{RsH}} \text{ ------------------------------(7.1)}$$

N_p = number of parallel solar module arranged

I_{ph} = Light-generated current or photocurrent

I_s = Cell saturation of dark current

q = 1.6*10^-19C (charge of electron)

N_s = number of series solar module arranged

R_s = Series resistance

K= 1.38*10^23J/K (Boltzmann’s constant)

T_c = Cell’s working temperature,

A= ideal factor

R_{SH} = shunt resistance

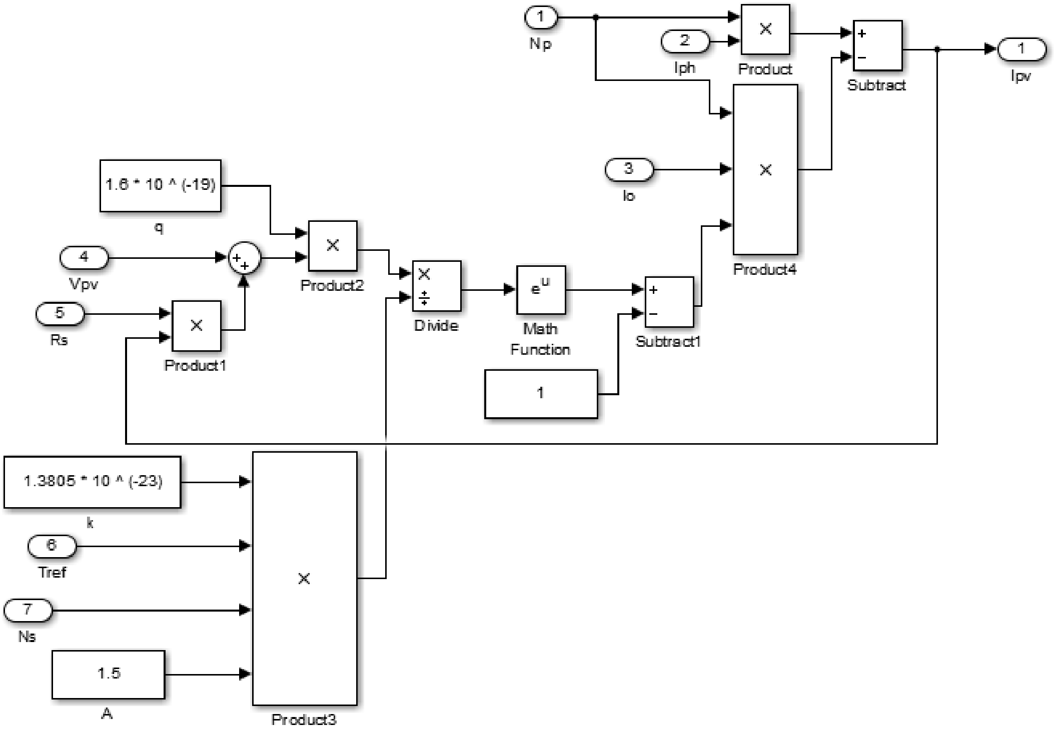


Figure7.5 PV current Matlab Simulation

The module saturation current varies with the cell temperature

$$Is = I\mathrm{RS} * \frac{Tc}{Tref}^{3} e^{\frac{q\mathrm{EG}(\frac{1}{Tref}-\frac{1}{Tc})}{kA}}$$ --------(7.3)

I_{RS} = Reverse saturation current at a reference temperature of a solar radiation

E_G = Bang energy of the semiconductor

A = The ideal factor dependent on PV technology

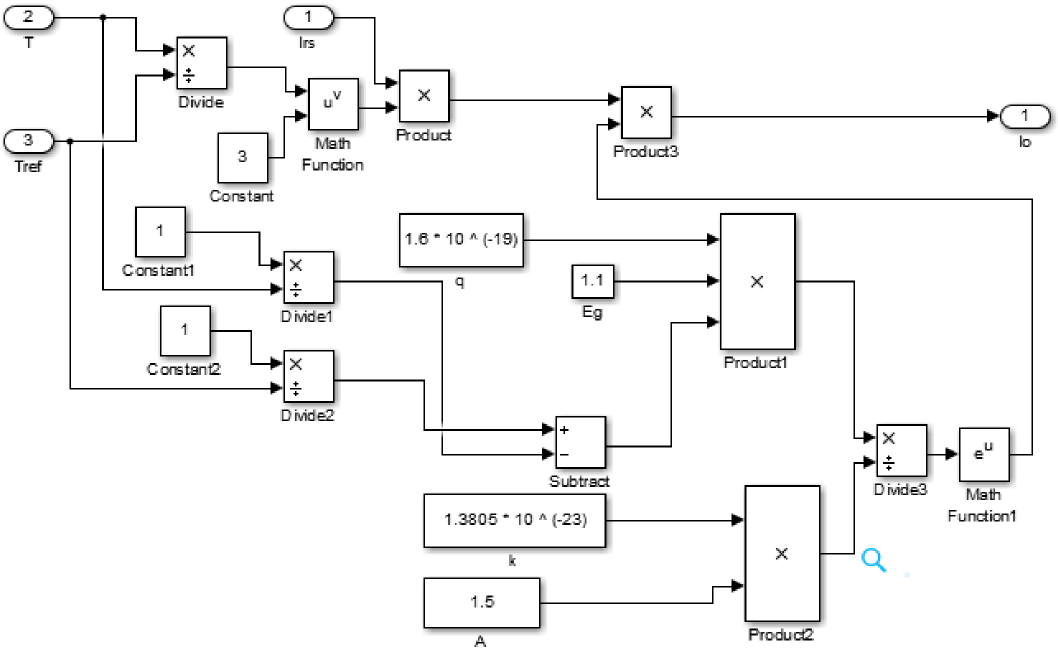


Figure7.7 Module saturation current Matlab Simulation

Since normally $I_{PH} >> I_S$ and ignoring the small diode and ground-leakage currents under zero short-circuit current I_{SC} is approximately equal to the photocurrent $I_{PH.}$

$$I_{PH} = I_{SC} \text{-----------------------------}(7.4)$$

On the other hand, the V_{OC} parameter is obtained by assuming the output current is zero. Given the PV open-circuit voltage V_{OC} at reference temperature and ignoring the shunt leakage current, the reverse saturation current at reference temperature can be approximately obtained as [20]

$$\mathrm{IRS} = \frac{\mathrm{ISC}}{e^{\frac{\mathrm{qVoc}}{\mathrm{NsKTcA}}}-1} \text{------------}(7.5)$$

Maximum power is defined as

$$\mathrm{Pmax} = \mathrm{VmaxImax} = \gamma\,\mathrm{VocIoc} \text{-------------------------------------}(7.6)$$

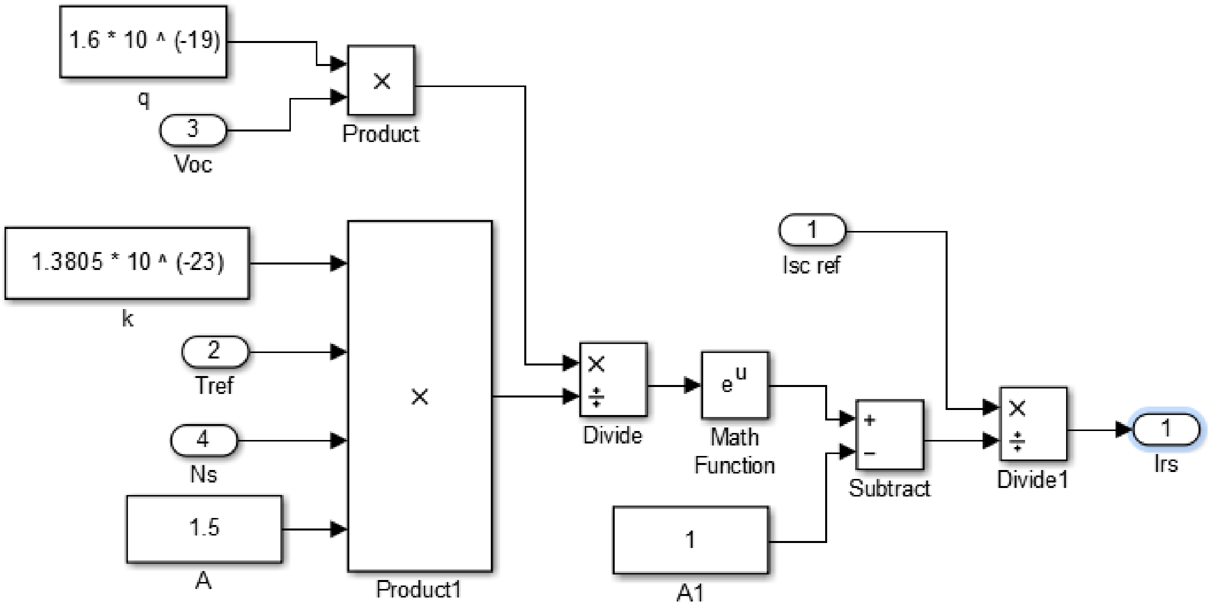


Figure 7.8 Reverse saturation current Matlab Simulation

Where V_{max} and I_{max} are terminal voltage and output current of PV module at maximum power point (MPP), and γ is the cell fill factor which is a measure of cell quality. Here consider γ is equal to 1.

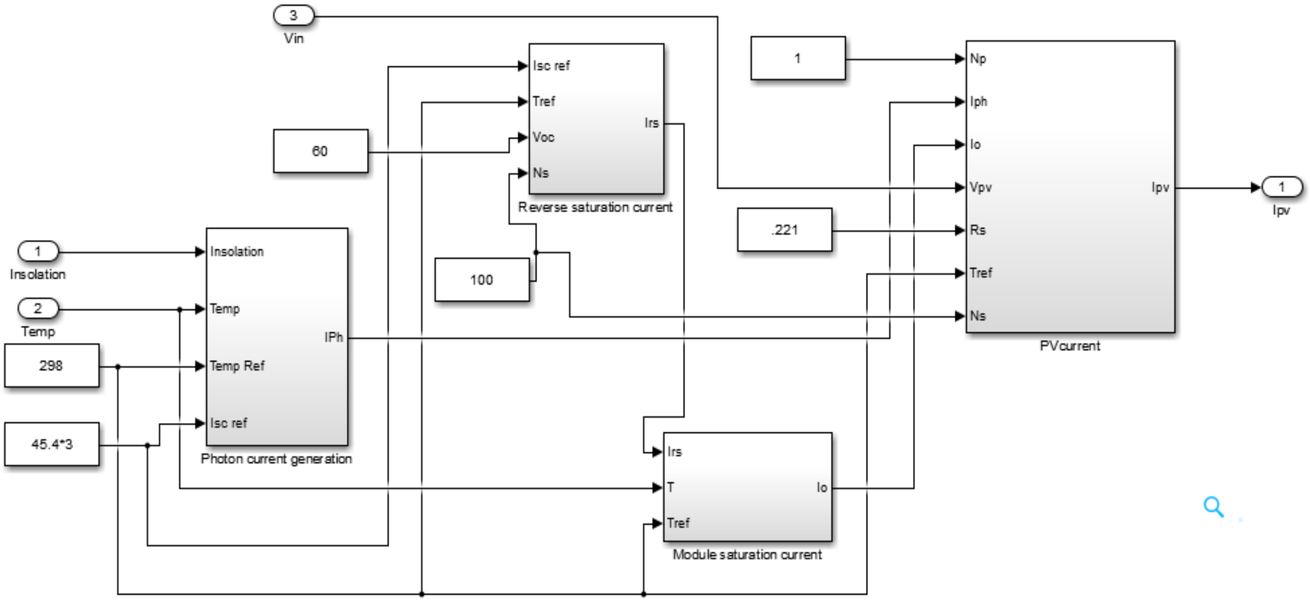


Figure 7.9 Solar Module Matlab Simulation model

8. POWER CONDITIONING CIRCUIT (DC-DC BOOST CONVERTER)

DC-DC converters are power electronic circuits that convert a DC voltage to a different DC voltage level, often providing a regulated output. The key in- gradient of MPPT hardware is a switch-mode DC-DC converter. It is widely used in DC power supplies and DC motor drives for the purpose of converting unregulated DC input into a controlled DC output at a desired voltage level. MPPT uses the same converter for a different purpose, regulating the input voltage at the PV Maximum Power Point (MPP) and providing load matching for the maximum power transfer. various DC-DC converter topologies used for MPPT applications are buck, boost, buck-boost, Single Ended Primary Inductor Converter (SEPIC) and cuk converter topologies.

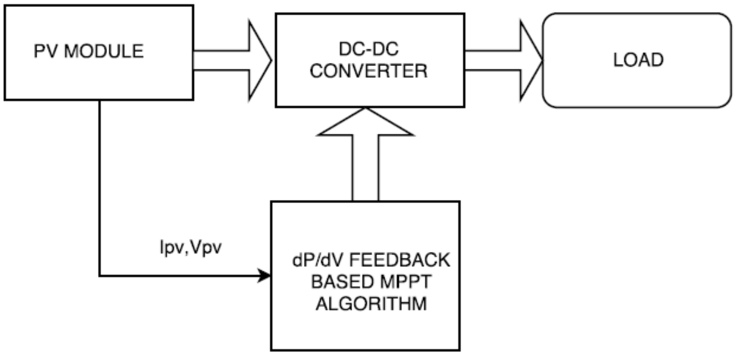


Fig. 8.1: System Architecture DC- DC converter

Table 8.1 shows the comparison of various DC-DC converters based on the output voltage polarity, efficiency and cost. Among the various converter topologies buck and boost converter topologies are widely used due to their high efficiency. Comparing the buck and boost converter topologies for PV applications, due to the presence of blocking diode in the boost converter, it will prevent the reverse current ow to the PV panel during night time and the value of filter capacitor requirement for boost converter is low compared to buck converter, these all advantages make boost converter suitable for PV applications. Fig.3.5 shows the circuit diagram of a boost converter. Figure 5.2 show block diagram of System Architecture DC- DC converter.

Converters	**Output Voltage Polarity**	**Efficiency**	**Cost**
Buck	Non Invert	Low Compared to Boost	High
Boost	Non Invert	High	Low
Buck Boost	Invert	Low	High
SEPIC	Non Invert	Medium	High

Table 8.1: Comparison of Various dc-dc Converters

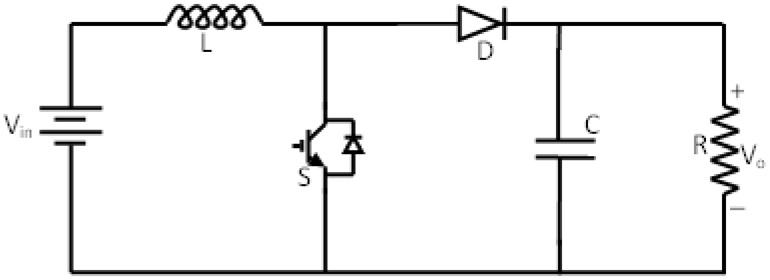


Fig. 8.2: DC-DC Boost Converter

The conversion ratio of boost converter is given by the following expression:

$$\frac{Vo}{Vin}=\frac{Iin}{Io}=\frac{1}{1-D}$$

D is the duty ratio and V_o,V_{in},I_in,I_o are input output voltage and current .

9. MAXIMUM POWER POINT TRACKING ALGORITHM

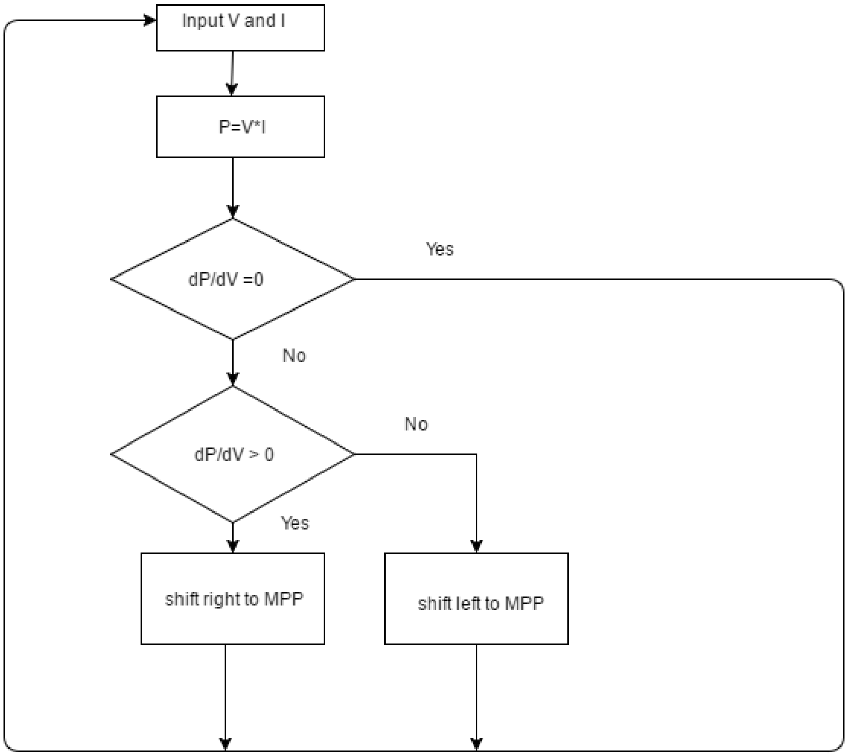
Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power it is capable of. A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel. MPPT is not a mechanical tracking system that physically moves the modules to make them point more directly at the sun. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Electrical circuits are designed in such a way that it can give loads to the photovoltaic cells and then convert the voltage, current, or frequency to suit other devices or systems. MPPT in such a case, solves the problem of choosing the best load to be given to the cells in order to get the most usable power out. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different.

When solar PV systems are deployed for practical applications, the I-V characteristics keeps on changing with radiance and temperature. Therefore, to increase the efficiency of the PV system it is desirable to operate them at the maximum power output. According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the source impedance of the circuit matches with the load impedance. Hence, the problem of tracking the maximum power point reduces to an impedance matching problem.

In this research to get maximum power, dP/dV feedback algorithm is used. From the PV graph we can understand the curve is like Gaussian curve. Figure 9.1 shows I-V and P-V characteristics of Solar Cell. P_m is the maximum power point which we need to track. In dP/dV algorithm calculates derivative of power with respect to the voltage. The current(I_{pv}) and voltage (V_{pv}) is measured and power is calculated. In Matlab, calculating the power with a delay and measuring the difference between actual power now, then we can get the derivative power. When the derivative power with respect to voltage equal to zero that is the maximum power point (MPP) P_m. Derivative power with respect to voltage is less than zero means that it is in the left side of MPP and we are trying to shift it into right until it becomes zero. Derivative power with respect to voltage is greater than zero means it is in the right side of MPP and we are trying to shift it into left it until becomes zero. [21] Power calculating using equation 4.6 $P_{max} = V_{max}*I_{max} = V_{ph}*I_{ph}$. Figure 9.2 shows matlab representation of dP/dV algorithm. dP/dV algorithm is coming from Incremental Conductance method.

$$\begin{gathered} dP/dV = 0 \text{ at MPP} \\ dP/dV > 0 \text{ left of MPP} \\ dP/dV < 0 \text{ right of MPP} \qquad \text{-----------------------}(9.1) \end{gathered}$$

Figure 9.1 shows the flowchart of dP/dV algorithm.



9.1 flowchart of dP/dV algorithm

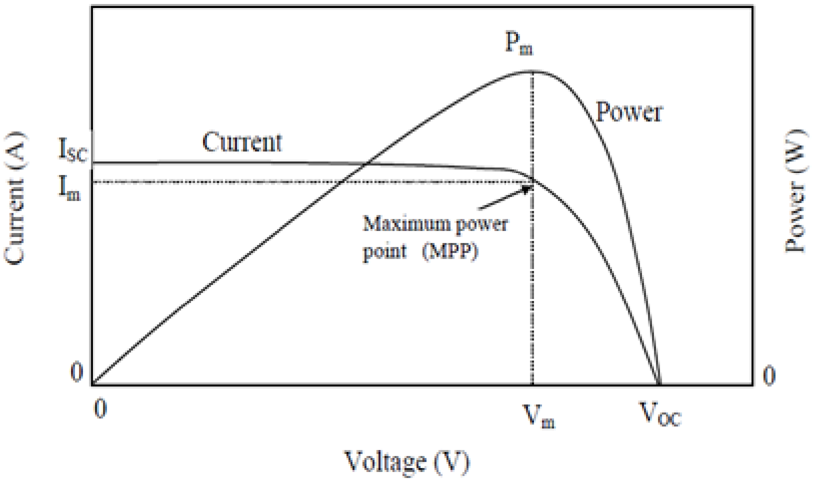


Fig. 9.2: I-V and P-V characteristics of Solar Cell

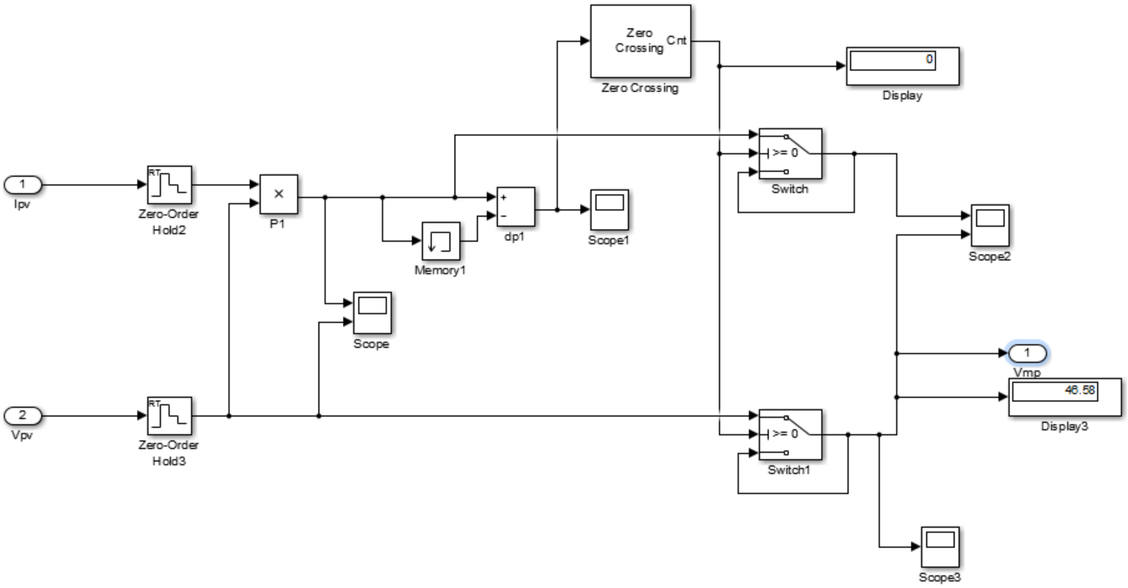


Figure 9.3 dP/dV algorithm matlab representation

The width of pulse width modulation (PWM) is adjusted automatically based on equation (9.1), such that the operating point moves towards the MPP. Usually a PI controller is used to adjust the duty ratio of the MPPT power converter. The PI controller gains are tuned while operating the system at a constant voltage equal to the standard test condition value of the MPP voltage. These gains are kept constant while the reference voltage is controlled by the MPPT algorithm. For direct duty ratio perturbation, the duty ratio of the MPPT converter is used directly as the control parameter.

Figure 9.3 shows Matlab Simulink representation of PI controller and PWM generation.

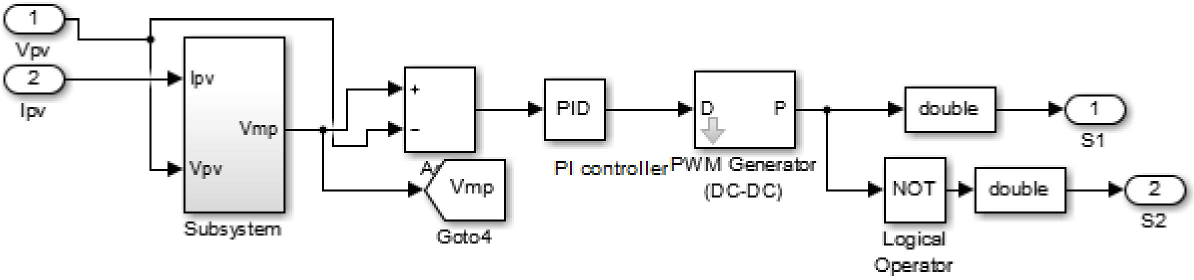


Figure 9.4: PWM signal generation Matlab Simulink representation

From the literature analysis we can understand the major drawback of dP/dV and incremental conductance method, that is the failure to track optimum power under partial shading conditions. In this research work using mechanical tracker to track irradiance in the solar panel we can avoid a part of shadow effect and achieve maximum efficiency using the MPPT algorithm.

10. SIMULATION RESULTS AND DISCUSSION

In this research work I am going to compare power output from the PV panel

- with and without tracking at a particular place
- power outputs at of two different places

Places are located using mainly five parameters: Time difference from GMT, Number of days from the start of a year (let’s say input 1 equal to January 1 and input 32 equal to Februry 1), Longitude, Latitude, Local time in 24 Hour clock. The two locations that I chose for the analysis are: Cochin, India and Kaunas, Lithuania. The input parameters in Matlab Simulink is given in table 1.

Place(location)	Kaunas(Lithuania)
Time difference from GMT in hours	3
No of days since the start of the year(date)	120(april 30)
Longitude	23.8924
Latitude	54.8969
Local Time in 24 hour format	12

Table 10.1: input parameters in Matlab Simulink to locate the place Kaunas

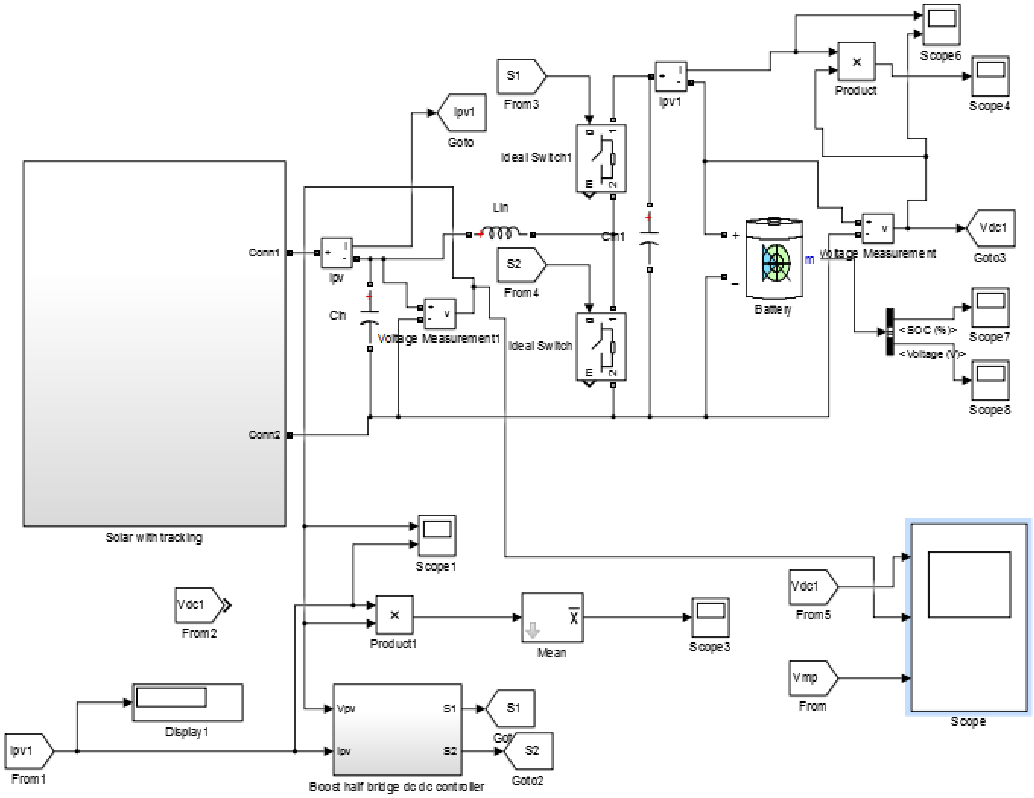


Figure 10.1 Matlab Simulink model of solar with tracking and mppt algorithm

From the above given input parameters, calculation of elevation angle, azimuth angle, zenith angle and intensity of the direct component of sunlight are performed. When we are using tracking, module irradiance input is dependent on azimuth and zenith angle. If we are not using tracking to calculate module irradiance, azimuth and zenith angle are not the input parameter for module irradiance block. Figure1 shows power output in Kaunas during April with tracking, it is almost 1750 units of power and Figure2. shows power output in Kaunas during April with tracking without tracking and it is almost 1450 units of power. It is almost like starting summer time in Kaunas so we can get more power output. In Figure.4 the output power in Kaunas after using MPPT and controller from output we can see it is more controlled and tracking the maximum power point. Here I used dP/dV feedback algorithm. Figure 10.1 shows Matlab Simulink model of solar with tracking and mppt algorithm.

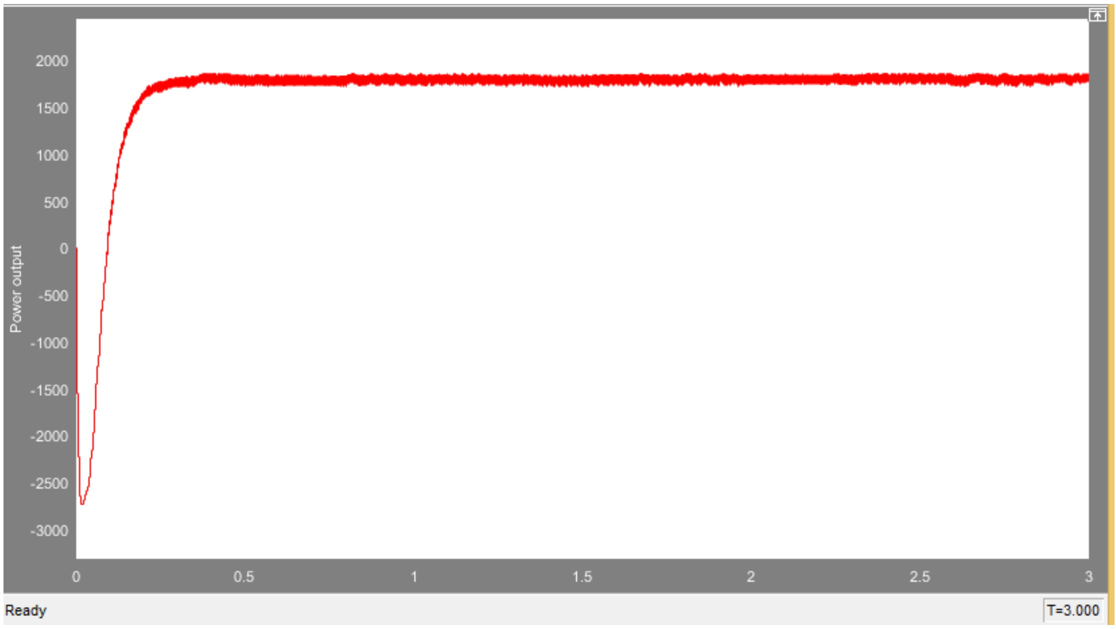


Figure 10.2 power output with tracker April 30 in Kaunas

Figure 10.2 shows the power output with tracker and MPPT in Kaunas, here we can see 1750 unit of power output. The power output when the tracker is used is higher than the output without the tracker. The power output without tracker is approximately 1450 units. The graph indicating output power without tracker can be seen in Figure 10.3

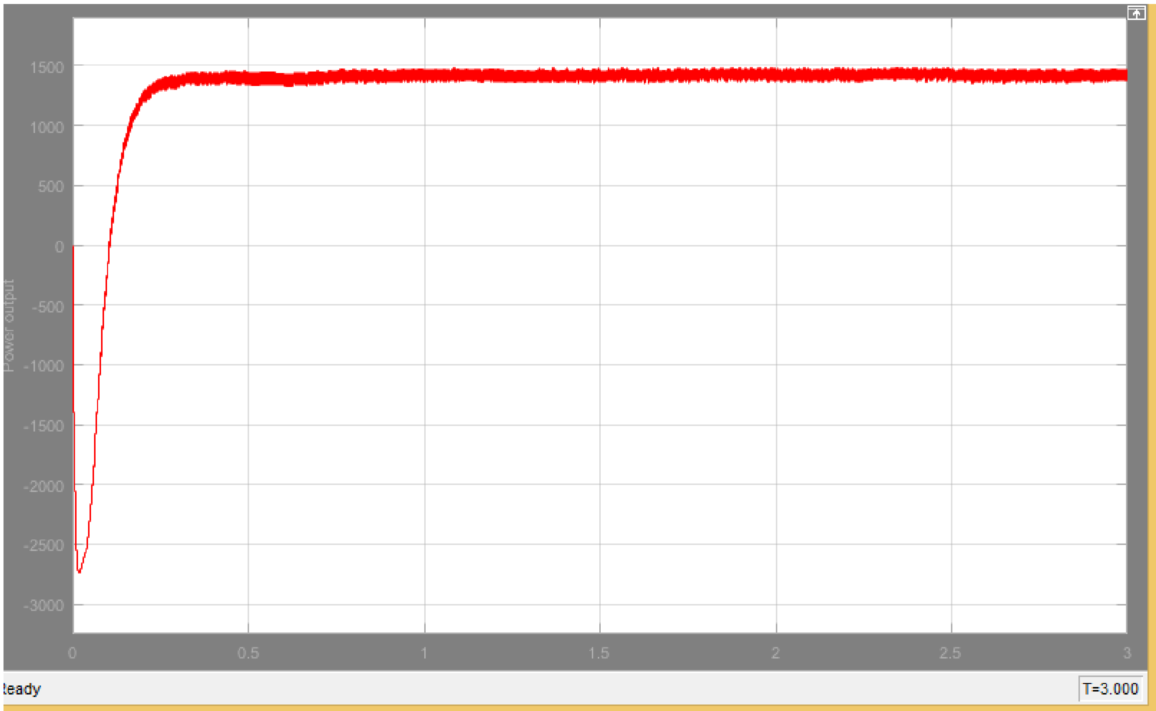


Fig 10.3 power without tracker april 30 in Kaunas

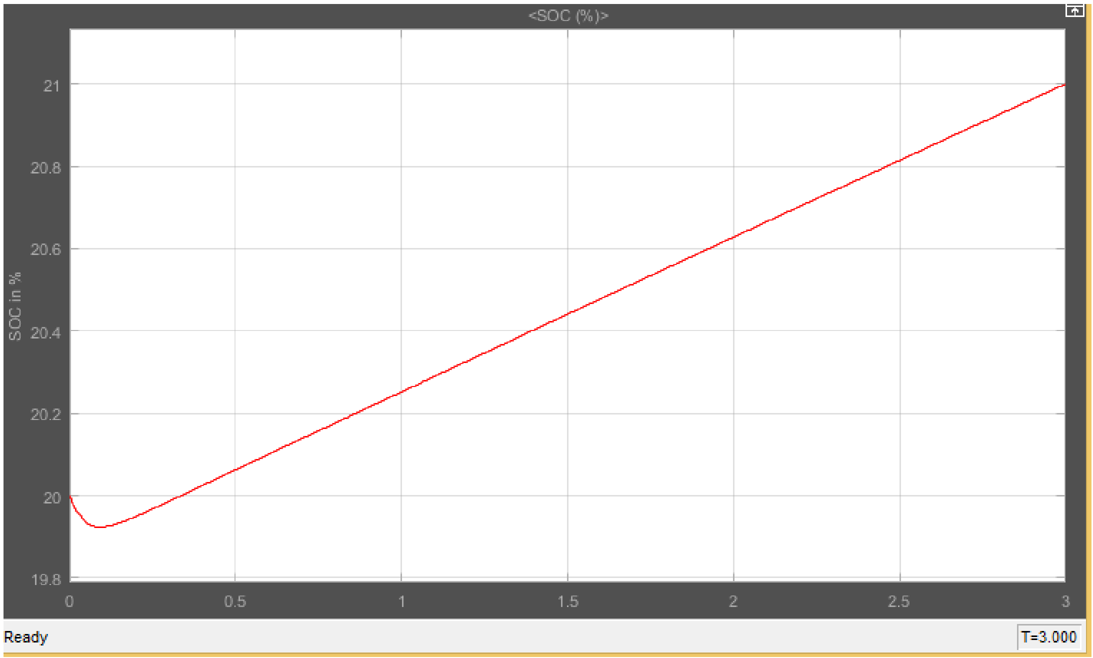


Figure 10.4 battery SOC in % with tracker.

The power obtained from solar panel is being used by the load. If the power obtained is higher than the power required by the load, the excess power will be stored into the battery. If the power obtained by the solar panel is lower than the power required by the load, the difference in power is taken from the battery. Initially while tracking, power obtained by the panel is less, hence some amount of power is taken from the battery and this is clearly shown in Figure 10.4, Comparing Figure 10.4 and figure 10.5, we can conclude that the battery charges more quickly when tracker is used.

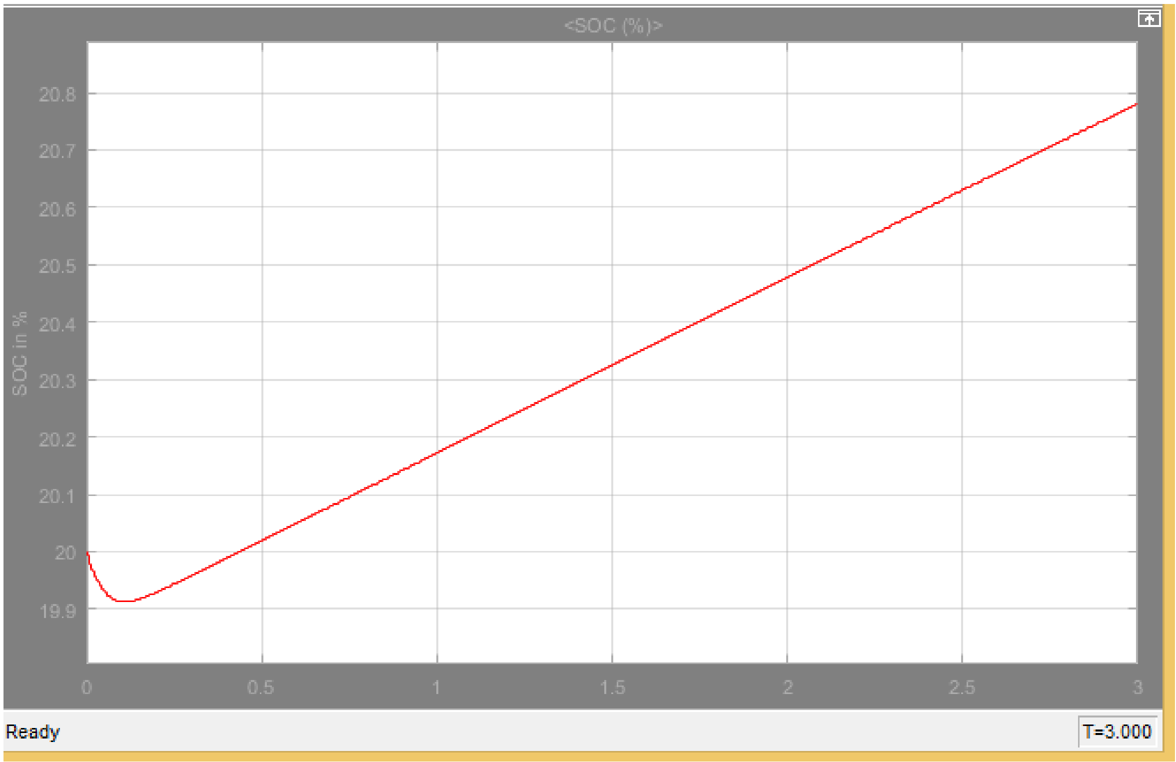


Figure 10.5 battery SOC in % without tracker

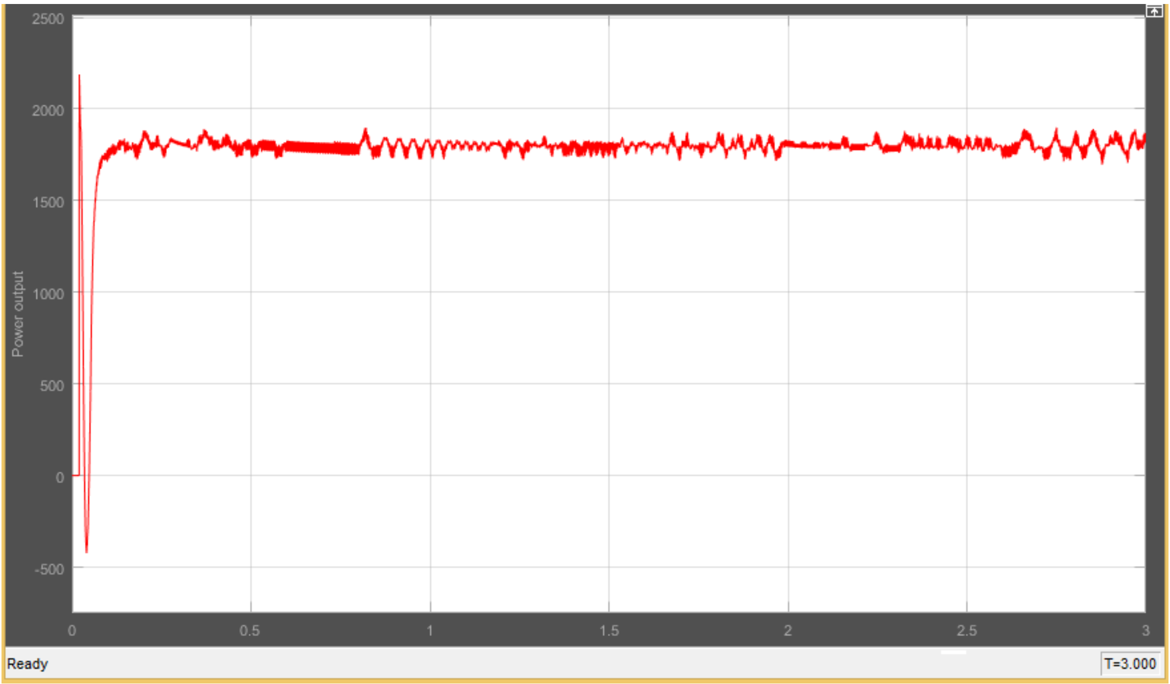


Figure10.6 power output without MPPT controller

Figure 10.2 shows the mean power output after controller is used. Figure 10.6 shows the mean power output before the controller is used. Comparing Figure 10. 1 and Figure 10.5, we can observe that the graph is figure 10.2 is more stable than that of figure 10.6. The mean power output has considerable amount of fluctuation as no controller is used. Figure 10.1 shows a stable output as MPPT controller is used.

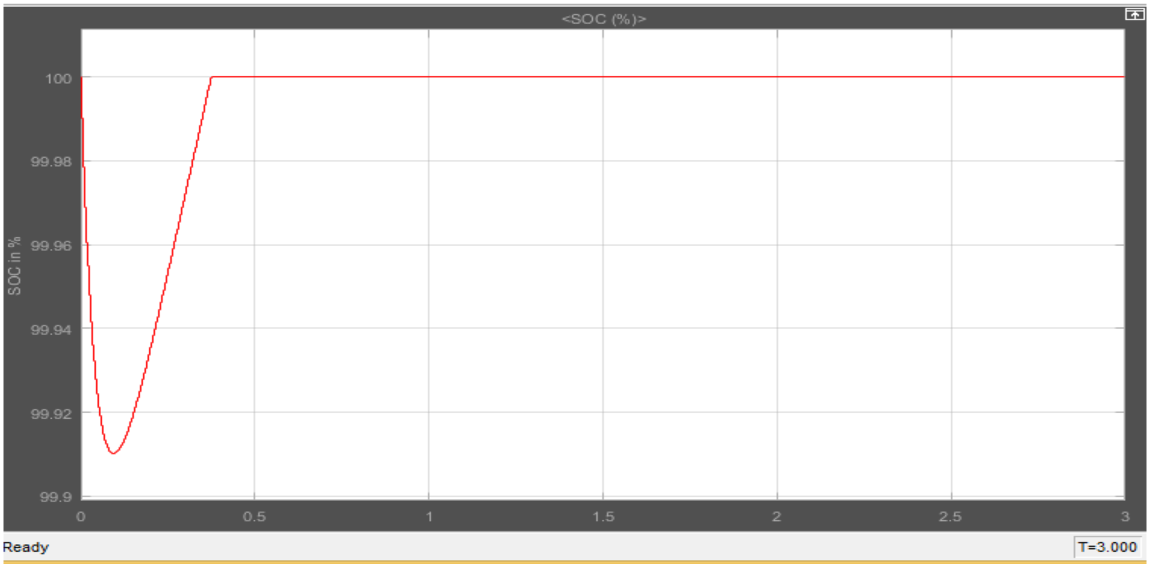


Figure 10.7: battery SOC in % when its fully charged

Figure 10.7 indicates the battery percentage level. Once the battery reaches 100%, it remains steady at that level and this can be seen in the above graph.

Table 10.2 shows parameters for locating a place Cochin in India. This place is near to equator so output power from PV panel is higher than Kaunas. Figure10.8 shows power output in Cochin during April with tracking, it is almost 1900 units of power and Figure10.9. shows power output in cochin during April with tracking without tracking and it is almost 1600 units of power. Figure 10.10 shows the power output before using MPPT controller and figure 10.8 and 10.9 are after using MPPT controller, because of higher solar irradiance fluctuation in power is more than in Cochin compare to Kaunas.

Locating Place	Cochin
Time difference from GMT in hours	5.50
No of days since the start of the year(date)	120(april 30)
Longitude	9.9392
Latitude	76.2596
Local Time in 24 hour format	12

Table 10.2: input parameters in Matlab Simulink locating the place Cochin

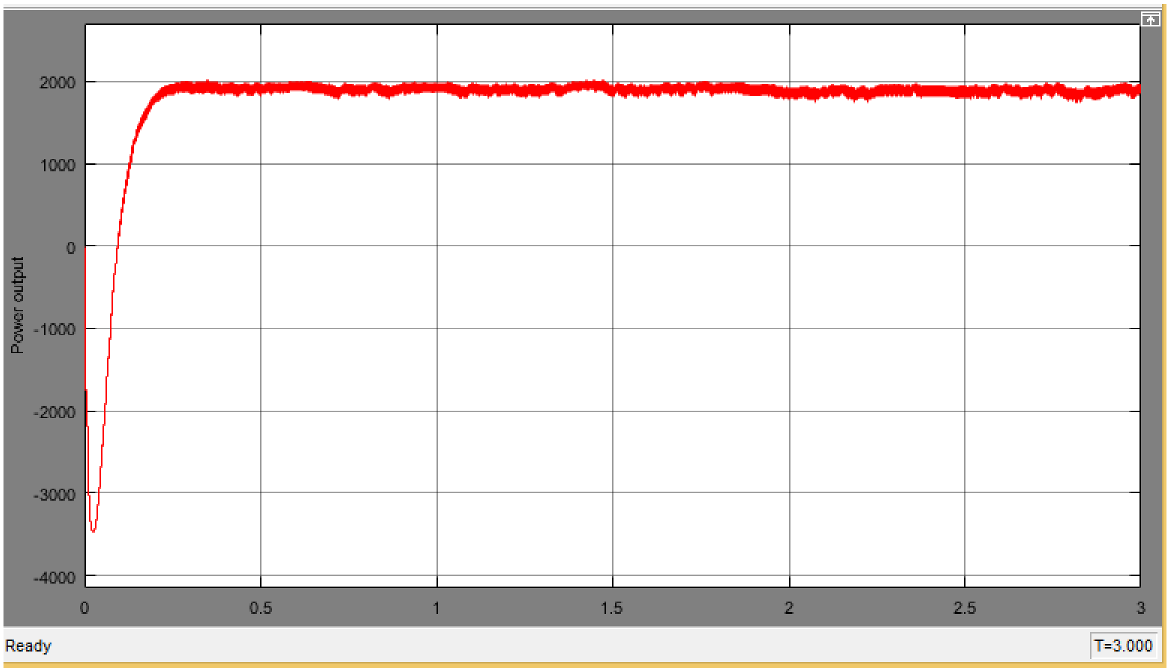


Figure 10.8 power output with tracker April 30 in Cochin at 13 hour

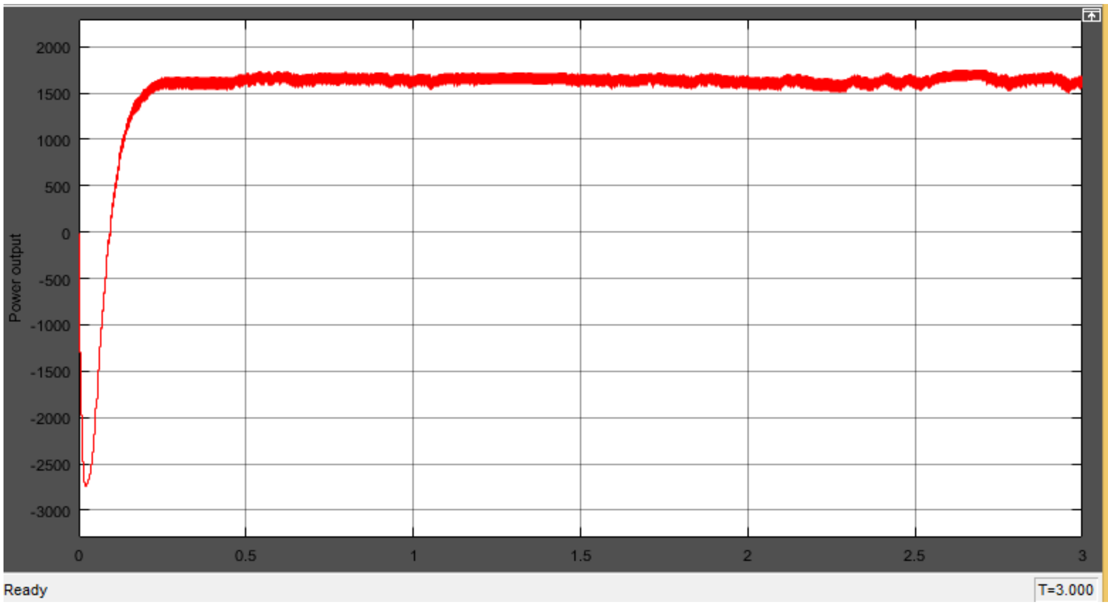


Figure 10.9 power output without tracker April 30 in Cochin

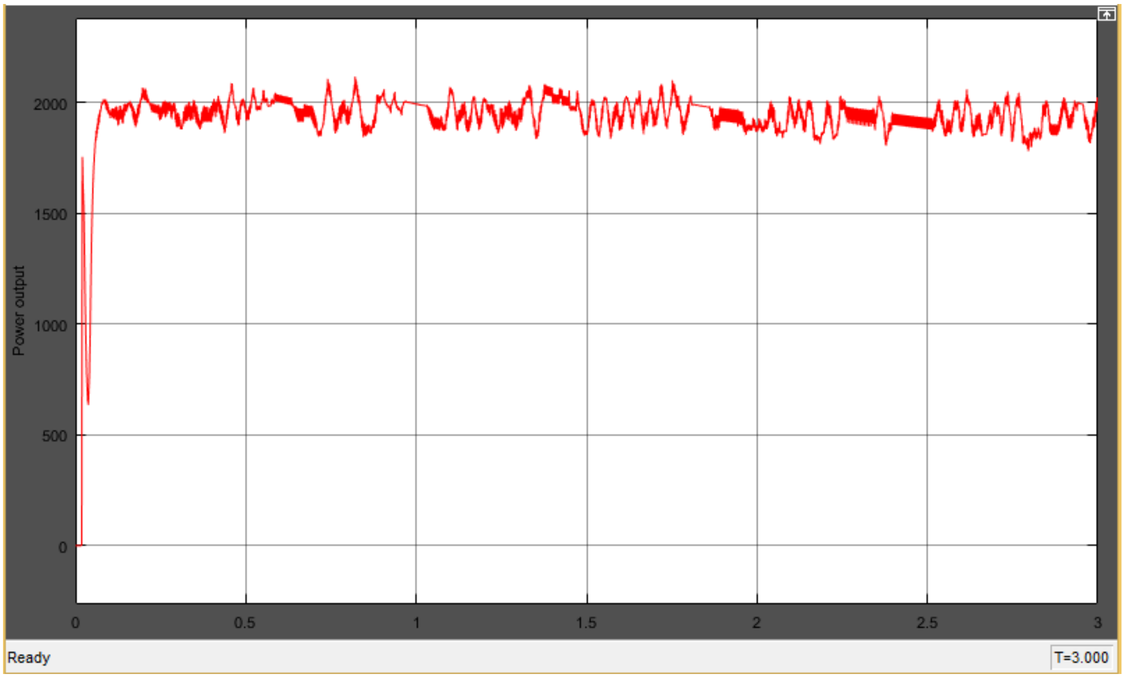


Figure 10.10 power output without MPPT controller in Cochin

In figure 10.12 shows power output in Cochin at 10 hour using tracker and MPPT.

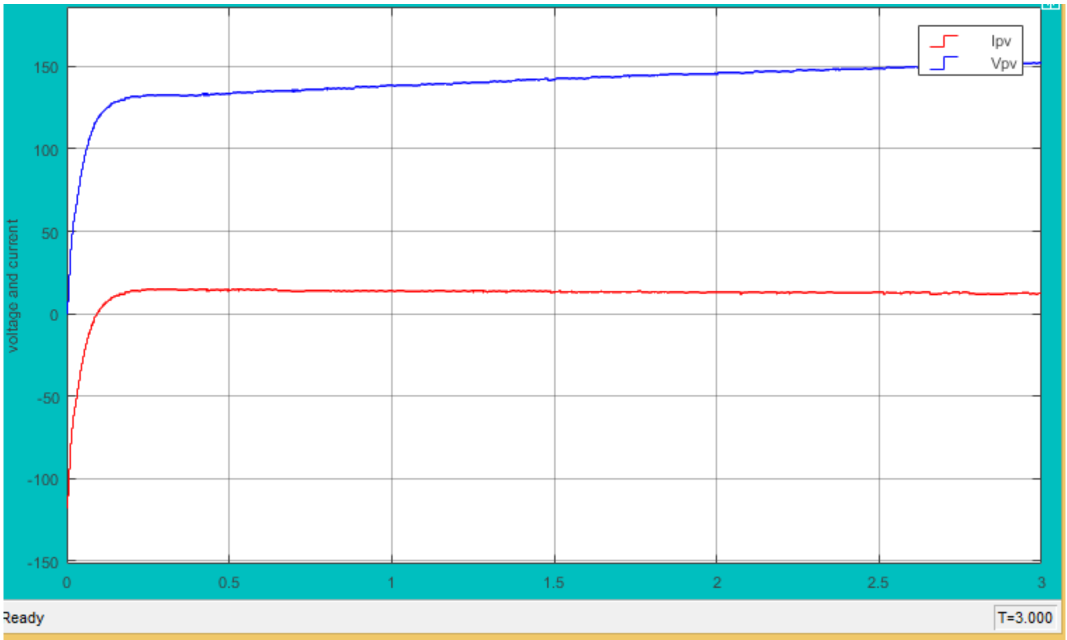


Figure 10.11 Voltage and current output to the storage

dP/dV algorithm is the variation of Incremental Conductance method. Figure 10.11 shows the current and voltage output of PV panel. From figure 10.11 found that dP/dV algorithm is also keeping change in voltage and change in current as zero. dP/dV method is also reduces the complex control circuitry.

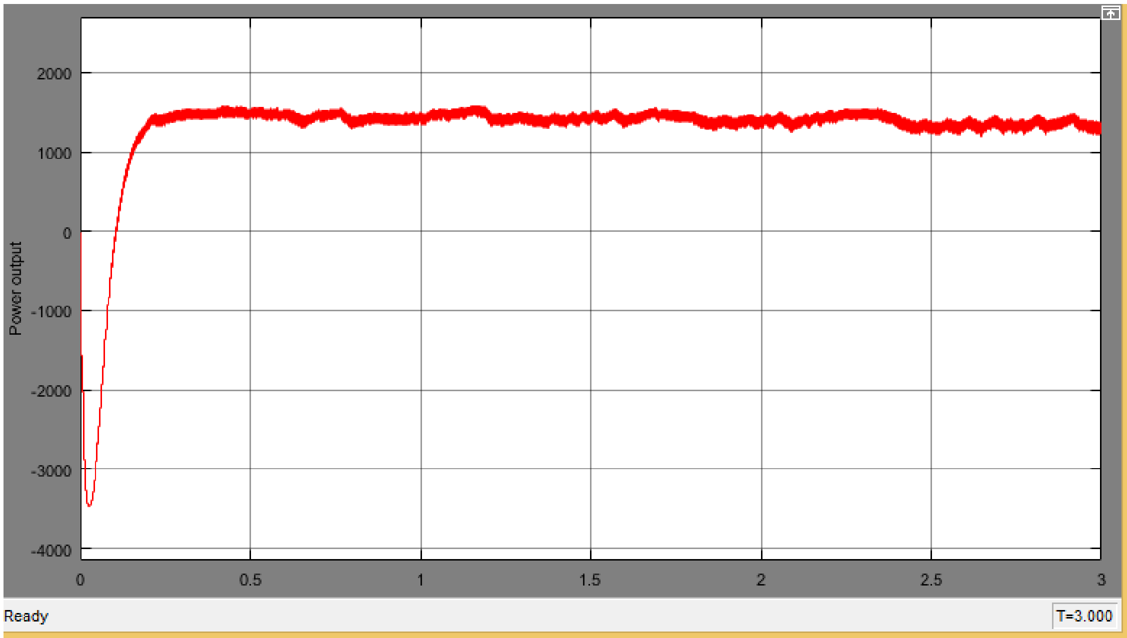


Figure 10.12 power output with tracker April 30 in Cochin at 10 hour

11. CONCLUSION AND RESULTS

- According to the literature MPPT is a useful technique to achieve the maximum efficiency for the solar panel. MPPT is a fully electronic system that varies the electric operating point of the module and hence the modules are able to deliver maximum available power.
- As per the conducted survey byusing a tracker for the solar panel enables to achieve more exposure to sunlight and produce higher power output.
- In MATLAB experimental investigation keeping the sun azimuth and module azimuth as equal and also tilt angle of the module and zenith angle of sun equal helps keep the solar panel directly parallel to sun, so the sunlight is always perpendicular to solar module and achieves maximum solar irradiance in the photovoltaic panel.
- PV system is modelled and simulated and maximum power from this module is tracked using axis tracker as well as dP/dV MPPT Algorithm. Clearly, MPPT increased the efficiency of the PV system by allowing it to operate at the point of maximum power. The simulation was conducted using the MATLAB/SIMULINK environment.
- It was investigated from the MATLAB result dP/dV algorithm is efficient.
- From figure 10.8 and 10.12 findings we can control the solar panel with time at regions where day night length is almost same. This region mostly falls around the equator.
- As shown in figure 10.8 and 10.9, it was found that the power output was higher for PV with the tracker. The difference was found to be close to 10 to 20% more than that without the tracker.
- From the MATLAB experimental investigation, it showed that without MPPT controller the power is unstable and fluctuating, but with MPPT controller the power is stable for 20-25% more and less fluctuating.

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