Modeling and Performance Analysis of Perturb and Observe (P&O), Incremental Conductance (IC), Fuzzy Logic, and Model Predictive MPPT Controllers Using a Boost Converter

K.Hareesh Reddy[1], R.Vijayasanthi[2], K.RamaSudha[3]
[1]M.Tech Student, [2]Assistant Professor, [3]Professor
Department of Electrical Engineering,Andhra University, Visakhapatnam,

Abstract:- In a photovoltaic module, there is a single operating point at which maximum output can be drawn from the module. This point at which maximum power can be obtained is known as "Maximum Power Point (MPP)". There is need to find the MPP and ensure that the point of operation is close to and around this point. The process of finding the MPP and always trying to keep the PV panel operating point at MPP is called "Maximum Power Point Tracking (MPPT)".The objective of the current paper is to model the PV cell and present the modeling of four different control techniques using MATLAB. The four control techniques are Perturb and Observe (P&O), Incremental Conductance (IC), Fuzzy Logic Control (FLC), and Model Predictive Control (MPC) algorithms. These algorithms are used to track the MPP of the PV module. All the control algorithms function together with a DC-DC converter, in this paper, a BOOST converter is used to perform all the simulations and maximum power point tracking. The P-V and I-V characteristics are drawn with the cell temperature kept constant. This paper also presents the study of the four control techniques and their performance analysis. The outcomes of these four techniques are compared, and relevant conclusions are drawn.

I. INTRODUCTION

With the growing population, the demand for electrical power is increasing thus increasing the consumption of conservative fossils such as coal, petroleum, etc. This in effect increases the depletion of these fossil fuels. And the electrical power generated from conventional resources has the effect of greenhouse gases. By using renewable energy resources, both the environmental concerns and depletion of fossil fuels are resolved, and these energies are abundant.

Solar energy is a good alternative for generating electricity from among the most renewable energy sources. PV modules, which have Maximum Power Points (MPP), directly convert solar energy to electrical energy. Given the advantages, due to the high cost of the PV module, the cost of solar energy is higher than the energy produced from fossil fuels. The extraction of the maximum power from the PV cell is a crucial factor in the optimal design of the PV system to minimize the overall cost.

Operating at the Maximum Power Point also increases the operating lifetime of the pv module. Maximum Power Point is a point at which maximum power can be obtained from the PV module when it is operated at this point. The maximum power drawn from the cell depends on the cell efficiency, ambient temperature, irradiation of the cell. In order to ensure the efficient operation of the cell,tracking the MPP is essential and known as Maximum Power Point Tracking (MPPT).

Conventional MPPT techniques are operated by sensing voltage and current from the PV module, calculating the output power, and thereby accordingly adjusting the duty cycle of the converter to achieve the MPP. In spite of having the same objectives, the various MPPT techniques differ in terms of convergence speed, oscillations around the MPP, cost, etc. The most popular techniques are Perturb and Observe (P&O), Incremental Conductance (IC), and the Hill Climbing Method (HC).

Advanced MPPT techniques have emerged, such asModel Predictive Control (MPT), Fuzzy Logic Control (FLC), etc have emerged. The use of these control techniques provide better results in monitoring the maximum power point than the conventional techniques as they produce a better performance under changing environmental conditions. But implementing these techniques is hectic because of the complexity involved in designing these techniques.

In the current paper, all four control techniques, i.e, Perturb and Observe, Incremental Conductance, Fuzzy Logic Control and Model Predictive Control are implemented to a PV module to track the MPP. The MPPT methods are compared based on the simulation of PhotoVoltaic systems and are modeled in inclusion with a DC-DC converter (Boost) and a load.

Modeling of PV Cell

Solar energy is convertedinto electrical energy by using Pv cells. The photons present in the sunlight, when they hit the solar panel, are absorbed by the electrons in the panel and get excited. The electrons get loose from the atoms and are allowed to move only in one direction, due to the special construction of the panel.

Hence a PV cell is modeled as a diode, which can be made of Silicon or Germanium. Since no PV cell is ideal, it contains losses, and these losses are modeled by shunt resistance (Rsh)andseries resistance (Rs). The series resistance (Rs) is caused by the current going through the emitter–base region of the solar cell, the contact resistance between the metal interface and silicon.The shunt resistance (Rsh) is typically due to the manufacturing defects in the solar panel. The higher the shunt resistance, the more the power is delivered to the load.

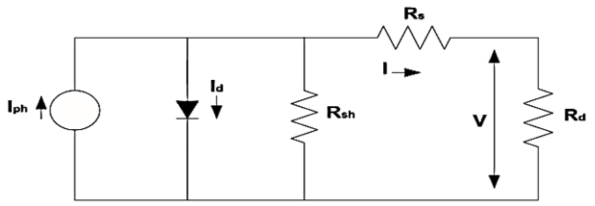


Figure 1: Equivalent circuit of the PV cell.

A PV cell can be modeled as a constant current source or a constant voltage source. They generate a current that is directly proportional to the amount of light that falls on the panel and adjust their output voltage as necessary to provide a constant current. Hence,a constant current source is used in the model and a single diode model is constructed to plot the P-V and I-V characteristics which is less complex when compared to the two diode model.

The I-V and P-V characteristics of the PV cell are given by the following equations:

$$I = N_p I_{ph} - N_p I_d \left[\exp\left(\frac{q\left(V + R_s I\right)}{kTAN_s} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (1)$$

$$I_d = I_0 \left[\frac{T}{T_0} \right]^3 \exp\left[\left(\frac{qE_g}{KA} \right) \left(\frac{1}{T_0} - \frac{1}{T} \right) \right] \quad (2)$$

$$I_{ph} = \left[I_{scr} + K_i \left(T - T_0 \right) \right] \left[\frac{S}{100} \right] \quad (3)$$

$$P = IV$$

$$P = N_p I_{ph} V - N_p I_d V \left[\exp\left(\frac{qV}{KTAN_s} \right) - 1 \right] \quad (4)$$

Where,

I_{ph} = PV cell photo current
I_d = Diode Reverse Saturation current
I = PV module output current
V = PV module output voltage
Ns = Number of cells in series
Np = Number of cells is parallel
q = charge of an electron
K = Boltzman’s constant
A = ideality factor
T = cell temperature in Kelvin
To = cell reference temperature in Kelvin
Io = reverse saturation current of the diode at To
Eg = Band gap energy of the semiconductor
Iscr = Short Circuit current of the cell at To
Ki = Short Circuit current temperature coefficient
S = Solar radiation

The general I-V and P-V characteristics at To of a PV cell are as follows:

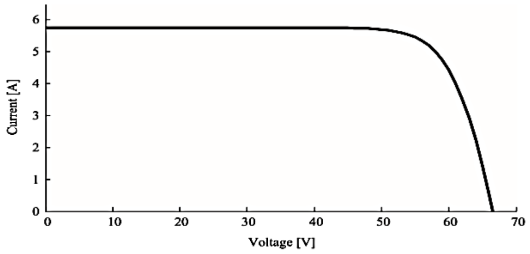


Figure 2. I-V Characteristics

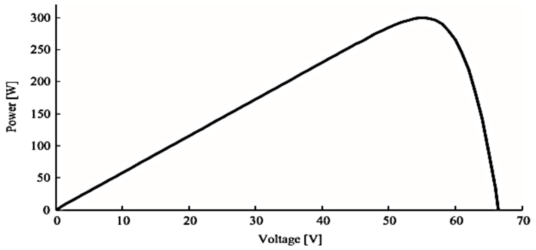


Figure 3. P-V Characteristics

Maximum Power Point Tracking(MPPT)

PV modules generate electricity by converting solar energy using PV cells. The amount of electrical energy generated by the PV cell generally depends on solar irradiance (S) and cell temperature (T). Although the electrical energy generated from the PV modules is clean and comes from a renewable resource, the capital investment is very high, although the maintenance costs are lower.

Maximum Power Point Tracking(MPPT) helps the solar panel to operate at the point where it delivers the maximum power to the load. The instantaneous voltages and currentsare sensed from the solar panel and fed to MPPT controller. A typical solar PV generation system with the MPPT looks like as below:

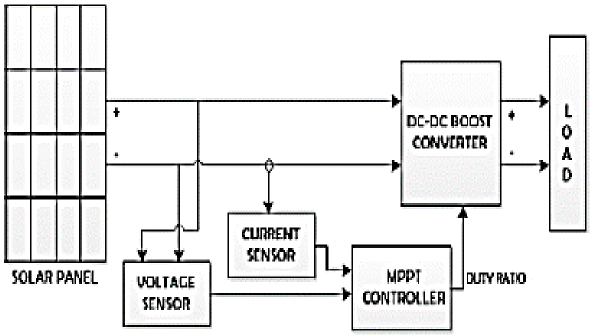


Figure 4. ***General solar PV generation with the MPPT controller***

Load Line

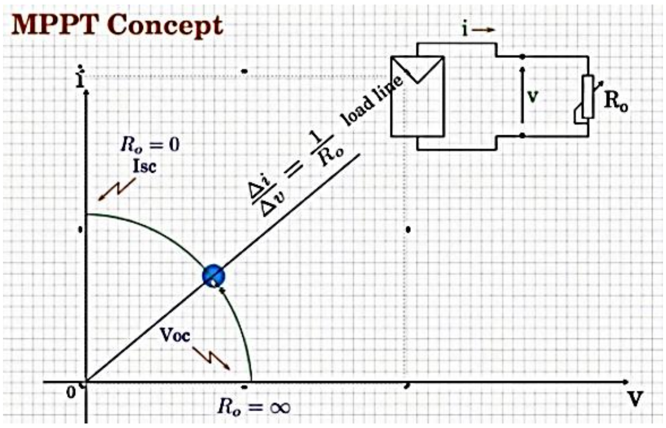


Figure 5. Load line

Let us consider a solar panel, as shown in the above figure, with an external load 'R_0' connected across the terminals of the panel. A load line is a straight line drawn on the 'I-V curve' of the solar panel. The slope of this straight line, since the y-axis is 'I' and the x-axis is 'V', is $\frac{dI}{dV}$. It is known that $\frac{dV}{dI} = R_0$. Hence, the load line slope is given by $\frac{dI}{dV} = \frac{1}{R_0}$.

The load line intersects the I-V curve at a point on the y-axis, the operating point is the 'I_{sc}'. At I_{sc}, the value of R_0 = 0.The operating point on the x-axis, which is the 'V_{oc}'. At the V_{oc} point, the value of $R_0 = \infty$.

So, for any operating point, it should represent the peak power that is being drawn. Now, consider a modified circuit with a converter in between the solar panel and the load.

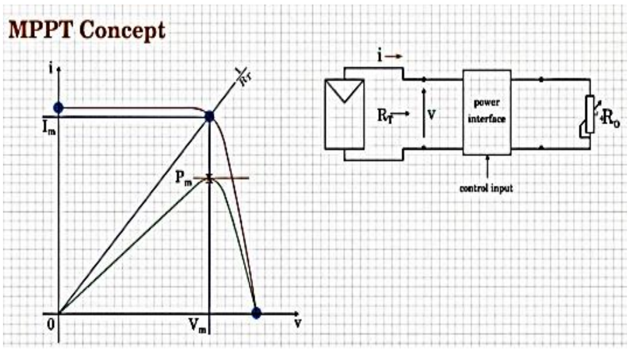


Figure 6. Modified load line

In the figure above, R_T is the terminal resistance seen from the PV side and R_0 is the terminal resistance seen from the converter side. The load line is drawn using R_T. Now, in the above I-V plot, the P-V plot is also superimposed. There should be a point of the P-V curve where the power is maximum and that point is representedas P_m.

The point on the I-V curve where the vertical line through P_m intersects is (I_m, V_m), where, I_m is the current at the maximum operating point and V_m is the voltage the maximum operating point. Hence, the point (I_m, V_m) is the maximum power point. If the load resistance R_0 is increased,and terminal resistance R_T also increases. Hence, the slope of the load line, $\frac{dI}{dV} = \frac{1}{R_T}$, decreases and Vice-Versa.Whenever the load R_0 changes, the slope of the load line changes, and it intersects the I-V curve at a point other than (I_m, V_m). Hence the electrical power delivered will always be less than P_m. Hence,a power interface is introduced between the solar panel terminals and the external load. If the load is a DC load, thenDC-DC converter power interface is required. The converter requires a control input. The converter with the control input maintains the input impedance of the converter at R_T, constant even though the external load changes.

So, whatever is the value of R_0, the control input is accordingly changed to maintain input impedance of the converter constant. Since the impedance R_T is constant, the slope of the load line is constant and so is the load line. As the load line is fixed, maximum power P_m can be drawn from the solar panel irrespective of the load. This process is called Maximum Power Point Tracking(MPPT), and needed to sense some quantities, and they are passed through a controller to generate the required control input so that R_T is maintained constant irrespective of the load R_0.

A DC-DC converter is used, which the control input duty cycle (D).In this paper a Boost converter is used to study all the control algorithms used in Maximum Power Point Tracking.

Input Impedance of a Boost Converter

A Boost converter consists of an uncontrolled switch like a diode and a controlled switch such as a MOSFET, BJT, etc.

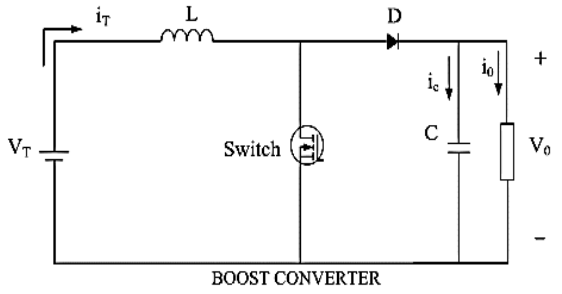


Figure 7. Boost Converter

The final equations are:

$$V_O = V_T\left(\frac{1}{1-D}\right) \quad (5)$$

$$I_O = I_T(1-D) \quad (6)$$

Hence, the relation between the load R_0 and input impedance of the converter, R_T is given by:

$$\frac{V_O}{I_O} = R_O = \left(\frac{V_T}{I_T(1-D)^2}\right) = \frac{R_T}{(1-D)^2} \quad (7)$$

$$R_T = R_O(1-D)^2 \quad (8)$$

As seen in equation (8), for a varying load R_0, the input impedance of boost converter R_T is maintained constant by varying duty cycle (D) accordingly. The load line is therefore fixed and panel operates at the maximum power point.

Now let us see the effect of the boost converter on the MPPT using the I-V curve. The slope of the load line is:

$$\frac{1}{R_T} = \frac{1}{R_O(1-D)^2} \quad (9)$$

From eq. (9), when D = 0, the slope of the load line is $\frac{1}{R_O}$ and when D=1, the slope of the load line is ∞.

The voltage and the current of the solar panel are sensed and are given as inputs to the MPPT controller. The output of the controller is the duty cycle (D) which is the controlled input of the Boost converter. The duty cycle (D) and the load R_0 are varying. The variation of the load is not in our control whereas the duty cycle can be controlled. Hence the duty cycle is controlled so the input impedance of the converter, R_T , is maintained at the maximum power point.

MPPT controller block is mainly concentrated. There are many algorithms by which Maximum Power Point can be obtained. Four of the algorithms are discussed in the coming chapter. They are namely the Perturb and Observe (P&O), the Incremental Conductance (IC), the Fuzzy Logic Controller (FLC), and the Model Predictive Controller (MPC).

Perturb and Observe (P&O) Method

In this algorithm, perturb the voltage (V) or current (I) of the panel and observe the power (P) delivered by the panel. If the operating voltage of the solar panel is perturbed and the power drawn from the panel increases, then the operating voltage is further perturbed in the same direction. If the power drawn from the panel decreases, this means that the operating point is shifting away from the MPP, then the operating voltage is perturbed in the opposite direction.

The algorithm is initialized with some arbitrary values of Voltage (V_{int}) and Current (I_{int}) of the panel and initial power (P_{int}) delivered by the panel is calculated. Initialize the duty cycle (D_{int}). Instantaneous voltage and current values are sensed and power delivered by the panel is calculated.

The power (P) and the voltage (V) are fed as inputs to the MPPT controller. The difference in the output power (ΔP) and the difference in the voltage (ΔV) is measured. The duty cycle of the converter is changed by applying a series of small, step-by-step perturbations, ΔD, to change the operating point of the panel.

Table 1.Updated duty cycle values

(ΔP)	(ΔV)	Updated duty cycle (D)
+ve	+ve	$D = D_{int} - \Delta D$
+ve	−ve	$D = D_{int} + \Delta D$
−ve	+ve	$D = D_{int} + \Delta D$
−ve	−ve	$D = D_{int} - \Delta D$

The key downsides of the P&O algorithm are the steady-state oscillations around the MPP, the tracking of MPP under rapidly changing environmental conditions, and the lower response speed.. Hence, the perturbation size determines the amplitude of the oscillations around the MPP and the convergence rate.

Incremental Conductance (IC) Method

To overcome the oscillations around the maximum power point, the incremental conductance method is introduced. From **Figure 3**, the slope of the P-V curve at the maximum power point is zero. The slope of the P-V curve to the right of the MPP is negative and is positive to the left of the MPP.

The equations corresponding to the incremental conductance algorithm are:

$$\frac{dP}{dV} = 0 \text{ at MPP} \qquad (10)$$

$$\frac{dP}{dV} = +ve \text{ to the left of MPP} \qquad (11)$$

$$\frac{dP}{dV} = -ve \text{ to the right of MPP} \qquad (12)$$

As $P = IV$,

$$\frac{dP}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V} \qquad (13)$$

Hence,

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \text{ at MPP} \qquad (14)$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V} \text{ to the left of MPP} \qquad (15)$$

$$\frac{\Delta I}{\Delta V} < \frac{-I}{V} \text{ to the right of MPP} \qquad (16)$$

The operating point of the solar panel tracks the maximum power point by measuring the instantaneous current and voltage values and comparing them with the change in current and voltage values as shown in equations (14), (15), and (16).

The steady state oscillations around the MPP are decreased by tracking the maximum power point using the IC algorithm. The main drawback of this method is the time taken by the operating point to reach the MPP and the computation involved in tracking the maximum power point.

Fuzzy Logic Controller to track the MPP of a solar panel

Fuzzy Logic controllers do not require the mathematical model of the system. Hence, this controller has advantages over conventional controllers when dealing with imprecise inputs. Since these controllers do not require accurate mathematical models, non-linearity can be easily dealt with using these systems. Hence, these controllers are more suited to non-linear systems.

In tracking the maximum power point of a solar panel using an FLC, the controller usually has two inputs. They are:

(i) Error (E)
(ii) Change in error (CE)

The error E is defined as follows:

$$E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \qquad (17)$$

And the change in error CE is given by:

$$CE(k) = E(k) - E(k-1) \qquad (18)$$

Where P and V represent the power and voltage sensed from the solar panel respectively. ‘k’ represents the current operating state and ‘k-1’ represents the previous operating state. The error E represents the position of the operating point, whether it is to the left or right of the maximum power point (MPP) and the change in error CE represents the moving direction of this operating point.

The crisp output is the change in the duty cycle (ΔD). The interfacing of the rules and the fuzzified inputs are by **Table 2** using the Mamdani approach. The defuzzification is done by the Center of Gravity (COG) method.

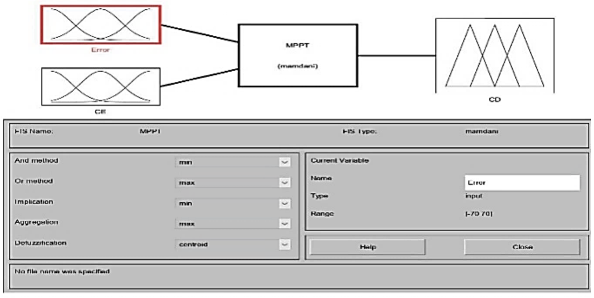
E and CE	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	PS
PS	NS	NS	ZE	ZE	ZE
PB	NB	NB	NB	ZE	ZE

Table 2.RULE BASE

The two crisp inputs, E and CE are fuzzified into five fuzzy sets, namely, NB: negative big, NS: negative small, ZE: zero error, PS: positive small, and PB: positive big. The output of the FLC is the change in the duty cycle (ΔD). This is converted to the duty cycle ratio $D(k)$ by

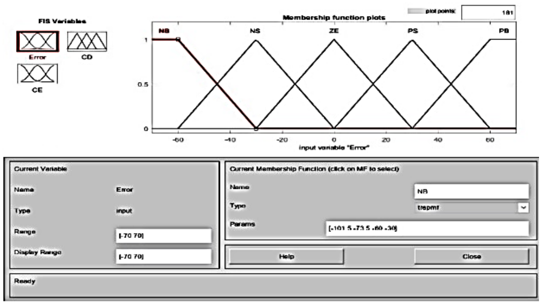
$$D(k) = D(k-1) + \Delta D \qquad (19)$$

The membership functions of the inputs and output of the FLC are shown below:



FIS Name: MPPT
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: Error
Type: input
Range: [-70 70]
No file name was specified

Figure 8. FIS file

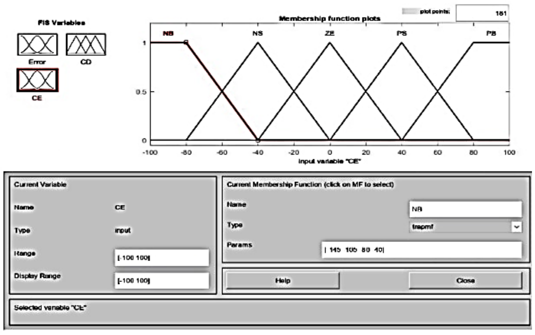


Current Variable
Name Error
Type input
Range [-70 70]
Display Range [-70 70]

Current Membership Function (click on MF to select)
Name NB
Type trapmf
Params [-101.5 -73.5 -60 -30]

Ready

Figure 9. Error (E)

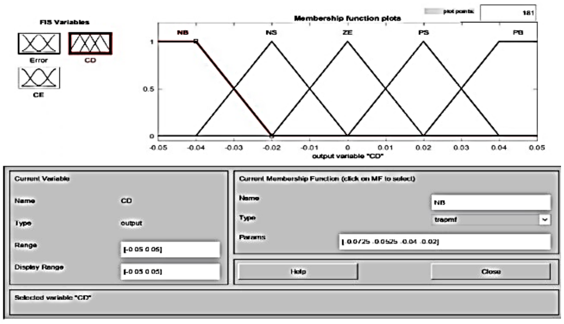


Current Variable
Name CE
Type input
Range [-100 100]
Display Range [-100 100]

Current Membership Function (click on MF to select)
Name NB
Type trapmf
Params [-145 -105 -80 -40]

Selected variable "CE"

Figure 10. Change in Error (CE)



Current Variable
Name CD
Type output
Range [-0.05 0.05]
Display Range [-0.05 0.05]

Current Membership Function (click on MF to select)
Name NB
Type trapmf
Params [-0.0725 -0.0525 -0.04 -0.02]

Selected variable "CD"

Figure 11. Change in Duty Cycle (CD)

Model Predictive Control (MPC) Method

Model Predictive Control uses the control and optimization tools at each sampling instant. The calculations are done at each time instant. MPC has several advantages over traditional control techniques. Some of them are:

(1) Multivariable
(2) Can handle input and output constraints effectively.
(3) Easily tuned compared to the traditional PI controllers.

Disadvantages include the requirement of an accurate mathematical model, computation involved, and computation time. The basic structure of a Model Predictive Controller is shown in **Fig 12.**

Fixed Step Size MPC is used in this paper. The total system consists of a PV array, a BOOST converter, and the switch of the boost converter is controlled by both MPPT and Model Predictive Control techniques.

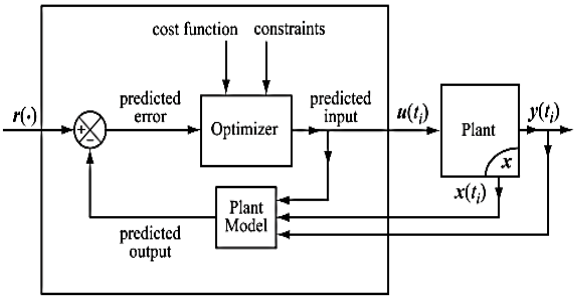


Figure12. Basic Structure of MPC.

The total system operates in this way, the PV array voltage (V_{pv}) is boosted up using the converted and using the corresponding factors required to track the maximum power point. The PV array voltage (V_{pv}), and the array current (I_{pv}) are the inputs to both MPPT and MPC. The MPPT controller generates the reference voltage (V^*), and the reference current (I^*), which are additionally fed to the predictive controller.

Hence, MPC takes V_{pv}, I_{pv}, V_C, I^*, and V^* as inputs, where, V_C is the output voltage of the converter. The output of the MPC is the switch condition (s) of the controller. When the switch is open, 's' is equal to '0' and 's' is equal to '1' when the switch is closed.

In tracking the MPP of the solar panel, an incremental conductance (IC) algorithm is used to generate the reference inputs, I^* and V^*. The Incremental conductance implemented is modified. The first modification is that both V^* and I^* are given as two of the inputs to the predictive controller and the second modification is that the reference outputs are defined as the increment of V_{pv} and I_{pv} rather than the increment of the previous reference output. The flowchart of the modified incremental conductance algorithm is shown in **Figure13.**

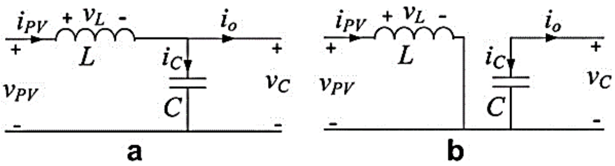


Figure 13. Boost converter circuit. (a) Switch Open (s=1). (b) Switch closed (s=0).

The controlled variables are the array current I_{pv} and the output voltage V_C. These are fed to MPC along with the reference inputs got from the modified INC algorithm. The future values of V_C and I_{pv} are predicted using the mathematical model of the Boost converter.

The corresponding equations are:

When the switch of the boost converter is open (s=1) as shown in **Figure 13.a,** the mathematical equations related to this mode are:

$$\frac{dI_{pv}}{dt} = \frac{-1}{L}V_c + \frac{1}{L}V_{pv} \qquad (20)$$

$$\frac{dV_c}{dt} = \frac{1}{C}I_{pv} - \frac{1}{RC}V_c \qquad (21)$$

When the switch is closed (s=0) as shown in **Figure13.b,** the mathematical equations corresponding to this mode are:

$$\frac{dI_{pv}}{dt} = \frac{1}{L}V_{pv} \qquad (22)$$

$$\frac{dV_c}{dt} = \frac{-1}{RC}V_c \qquad (23)$$

The continuous time equations are converted to discrete time equations. The equations in discrete time are, sampling time T_s are:

When the switch is open,

$$I_{pv}(k+1) = I_{pv}(k) - \frac{T_s}{L}V_c(k) + \frac{T_s}{L}V_{pv}(k) \qquad (24)$$

$$V_c(k+1) = \frac{T_s}{C}I_{pv}(k) + \left(1 - \frac{T_s}{RC}\right)V_c(k) \qquad (25)$$

When the switch is closed,

$$I_{pv}(k+1) = I_{pv}(k) + \frac{T_s}{L}V_{pv}(k) \qquad (26)$$

$$V_c(k+1) = \left(1 - \frac{T_s}{RC}\right)V_c(k) \qquad (27)$$

$$V_{pv}(k+1) = V_c(k+1)(1-D) \qquad (28)$$

D = Duty Cycle Ratio.

The above discrete equations represented in state space representation with the state of the switch considered is given as:

$$\begin{bmatrix} V_c(k+1) \\ I_{pv}(k+1) \end{bmatrix} = \begin{bmatrix} s\frac{T_s}{C} & 1 - \frac{T_S}{RC} \\ 1 & -s\frac{T_s}{L} \end{bmatrix} \begin{bmatrix} V_c(k) \\ I_{pv}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{T_s}{L} \end{bmatrix} V_{pc}(k) \qquad (29)$$

One-step horizon prediction is done in this paper. The output from the MPC block is fed to optimizer which consists of a cost function. Designing the cost function is key to designing the model predictive controller. The cost function is evaluated and the output of the cost function is fed to the switch. The cost function in this paper is defined as below:

$$J_{s=n}^{n=0,1} = w_a \,|\, I_{pv,s=n}(k+1) - I^* \,|\, + w_b \,|\, V_{pv,s=n}(k+1) - V^* \,| \qquad (30)$$

Where w_a and w_b are the parameter with some fixed value.

II. SIMULATION RESULTS

The SIMULINK model of the PV Cell is shown in **Figure 14**and the corresponding P-V and I-V curves are shown in **Figure 15**and **Figure16.**

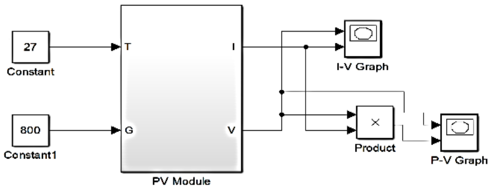


Figure 24. PV Cell Simulink Model

The corresponding PV cell parameters are shown in **Table 3.**

I_d	Diode Reverse Saturation Current	1.13×10^{-6}(A)
E_g	Band gap energy of the semiconductor	1.16eV
A	Ideality Factor	1
q	Charge of an electron	1.6×10^{-19}C
N_s	Number of cells in series	1
N_p	Number of cells in parallel	1
T_o	Cell reference temperature in Kelvin	298K
S	Solar Irradiation	800
R_s	Series Resistance	2.48Ω
R_p	Parallel Resistance	8.7Ω
K_i	Short Circuit Current Temperature Coefficient	1.96(mA / k)

Table 3. Parameters of PV cell

The Simulink model of implementing the MPPT algorithms to solar array is shown in the **Fig 17**

The corresponding I-V and P-V curves are shown in **Fig 18, 19, 20,21**

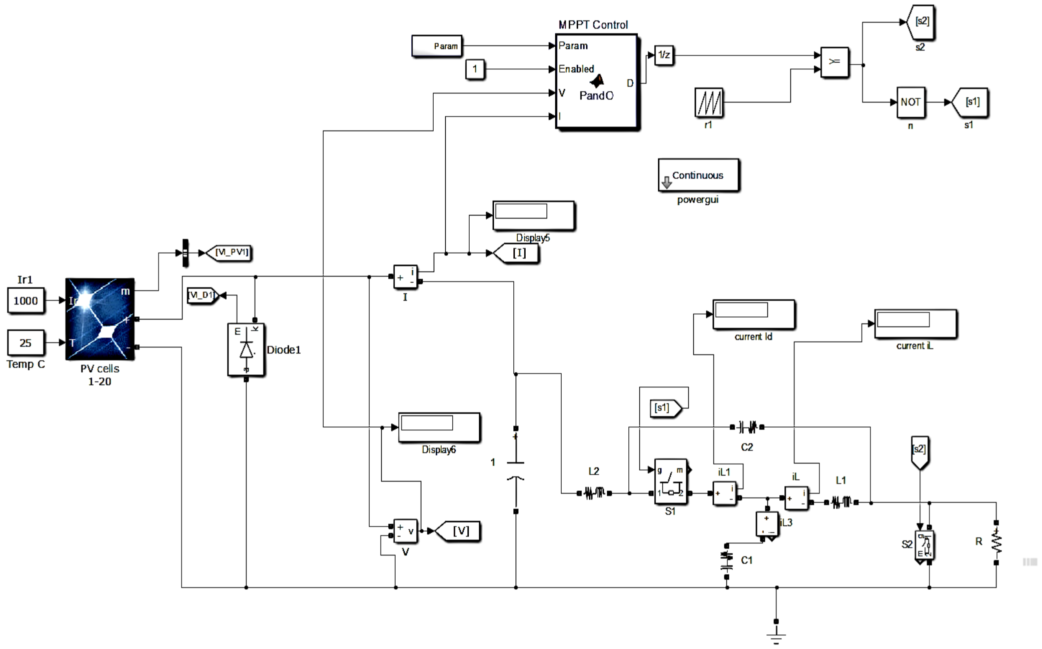


Figure 17. Simulink Model of implementing P&O

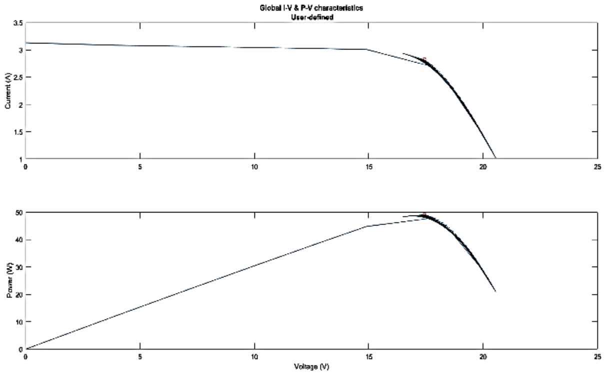


Figure 18. I-V and P-V curves using P&O

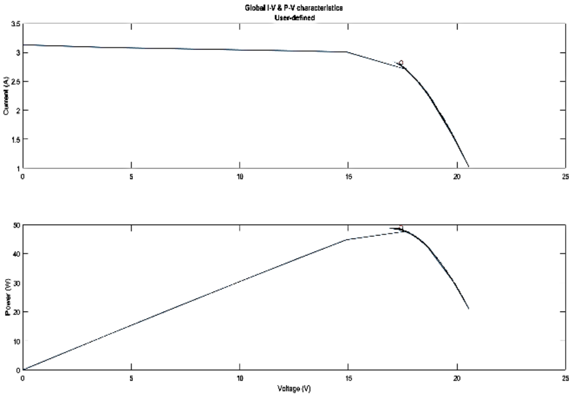


Figure 19. I-V and P-V curve using IC

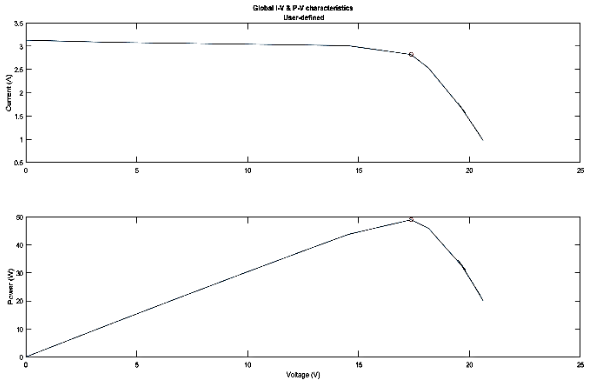


Figure 20. I-V and P-V curve using FLC

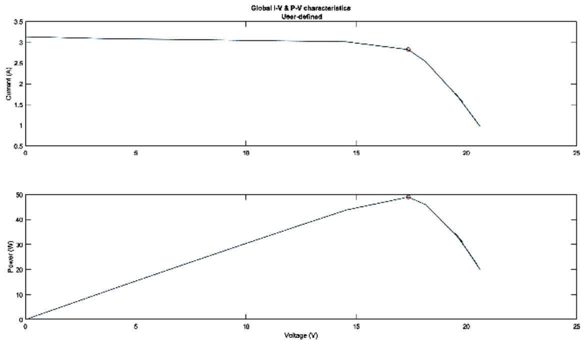


Figure 21. I-V and P-V curve using MPC

From the above shown I-V and P-V plots, it can be interpreted that the disturbance at the Maximum Power Point (MPP) is maximum for P&O, then followed by IC, then MPC and least in FLC

Each simulation is run for a time period of 3 seconds. The time taken by each algorithm is shown in the **Table 4.**

CONTROLLER/ METHOD	**TIME TAKEN (min)**
Perturb and Observe (P&O)	**8.50797**
Incremental Conductance (IC)	**8.82712**
Fuzzy Logic Controller (FLC)	**7.28085**
Model Predictive Controller (MPC)	**7.97241**

Table 4. Time elapsed

III. CONCLUSION

This paper presents the performance analysis of the Fuzzy Logic Controller (FLC) and Model Predictive Controller (MPC), which are compared with the traditional Perturb and Observe (P&O) and Incremental Conductance (IC) algorithms in tracking the Maximum Power Point Tracking (MPPT) of a solar panel. In general, choosing a controller depends on not just performance analysis, but on various other factors. When one requires a cheap and least complex controller, P&O suits the best for this purpose. If one prefers a controller that has moderate complexity and oscillations at MPP, then IC serves this purpose. If one needs fewer oscillations with a fast converging rate, an FLC suits the best. But FLC comes with more complexity and cost. MPC serves a better purpose when compared to P&O and IC, but the convergence rate is less than that of an FLC. MPC suits the most when there are constraints on the equations. Hence, when it comes to cost, then P&O suits them best and FLC suits the best when it comes to the convergence rate and oscillations at Maximum Power Point (MPP).

REFERENCES

[1]. A.Belkaid , JP.Gaubert , A.Gherbi , L.Rahmani, "Maximum power point tracking for photovoltaic systems with boost converter sliding mode control", In IEEE 23rd international symposium on industrial electronics (ISIE), Istanbul, Turkey, 1–4 June. p. 556–61.
[2]. Lazzard: ‘Lazard's levelized cost of energy analysis-version 8.0’, September 2014
[3]. Abbes, D., Martinez, A., Champenois, G.: ‘Eco-design optimisation of an autonomous hybrid wind-photovoltaic system with battery storage’, IET Renew. Power Gener., 2012, 6, pp. 358–371
[4]. Dagdougui, H., Ouammi, A., Dessaint, L., et al.: ‘Global energy management system for cooperative networked residential green buildings’, IET Renew. Power Gener., 2016, 10, pp. 1237–1244
[5]. Esterly, S., Gelman, R.: ‘Renewable Energy Data Book’. National Renewable Energy Laboratory (NREL), Washington, DC, 2013
[6]. Ransome, S.: ‘Worldwide photovoltaic energy yield sensitivity from a variety of input losses’, IET Renew. Power Gener., 2015, 9, pp. 398–404