IJDACR
ISSN: 2319-4863

IJDACR
International Journal Of Digital Application & Contemporary Research

International Journal of Digital Application & Contemporary Research
Website: www.ijdacr.com (Volume 7, Issue 02, September 2018)

Comparative Analysis of Maximum Power Point Controlling Techniques for Stand Alone PV System

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Abstract – **The photovoltaic systems used in the decentralized production of electric energy have undergone significant expansion during the last decade. On the other hand, there are two main shortcomings of PV system, namely the low conversion efficiency of PV modules and the high installation cost for the same. Moreover, the PV system shows nonlinear characteristics that depends on weather conditions.**

In this paper, standalone PV system is analyzed with different Maximum Power Point controlling techniques i.e. Perturb and Observe, Incremental Conductance & Fuzzy Logic Control, to study various parameters like settling time, oscillation around maximum power point and selection criteria of DC-DC converter. The PV array's output is supplied to the load after being conditioned by DC-DC boost converter.

The maximum power point tracking is essentially a load matching problem. When the load at converter end is fixed and the duty cycle of the converter is varied which in turns varies the effective load on the PV system, there by changing the slope of the load line and shifting the operating point and fixing it at the MPP, maximum power can be accomplished from the PV array. Selection criteria of DC-DC converter is important because DC-DC converter decides tracking and non-tracking region which is discussed in detail.

Keywords –**DC-DC converter, Fuzzy Logic Control, Incremental Conductance, MPPT, Perturb and Observe, PV array.**

I. Introduction

The conventional sources of energy are rapidly depleting. Moreover, the cost of energy is rising and therefore photovoltaic system is a promising alternative. They are abundant, pollution free, distributed throughout the earth and recyclable. The hindrance factor is its high installation cost and low conversion efficiency. Therefore, the aim is to increase the efficiency and power output of the system. PV arrays consist of parallel and series combination of PV cells that are used to generate electrical power depending upon the atmospheric conditions, such as solar radiation and temperature. Hence, it is necessary to couple the PV array with a DC-DC converter [1-6].

Photovoltaic electrical systems are those, which convert the energy of photons directly into electrical energy. The output power of such a system is highly sensitive to the environmental parameters, such as radiation and temperature. Hence, the maximum power that can be extracted from a panel also changes with change in these parameters. In order to ensure maximum extraction of power from a PV panel under varying environmental conditions, load should be changed in accordance with changing environmental parameters, hence the operating point always lies at the maximum power point.

Since, practically it is not possible to change the load time to time, there must be some interfacing circuit in between the PV panel and the load, which can change the load as seen from the side of PV terminals. As the output of PV panel is of DC in nature, generally switched mode power converters (DC to DC converters) are used as the interfacing circuit. The operating point is changed by varying the duty-cycle of these power converters. There are so many techniques in literature according to which the duty-cycle of these converters can be changed to track the maximum power point [1-7].

II. Maximum Power Point Tracking Techniques

The efficiency of a photovoltaic system is low, since the output power of the PV array depends on various environmental conditions such as temperature and solar radiation, that's why maximum power point fluctuates with change in radiation and temperature. Therefore, the need of a system to condition the output power of the PV array before supplying it to the domestic loads is necessary. Figure 1 represents a block diagram showing the use of a converter for PV energy system. The PV array output is supplied

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ISSN: 2319-4863

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to the load after being conditioned by DC-DC converter.

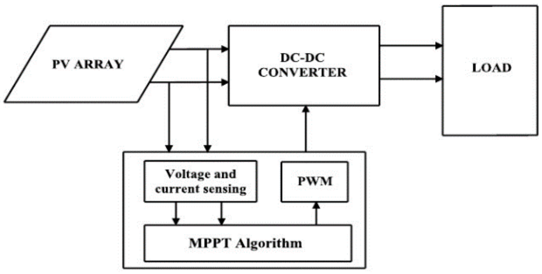

Figure 1: Block diagram of maximum power point tracking with DC-DC converter [8]

Maximum power point (MPP) is an operating point on either I-V or P-V characteristic curve of a PV array. It is that point of operation, where the power supplied to the load is maximum. From maximum power transfer theorem, when the load of the converter is fixed and the duty cycle of the converter is varied which in turns varies the effective load on the PV system, maximum power can be achieved from the PV system. In this way, by changing the slope of the load line, shifting the operating point and fixing it at the MPP, maximum power can be achieved. The concept of maximum power point tracking is shown in Figure 2 [8].

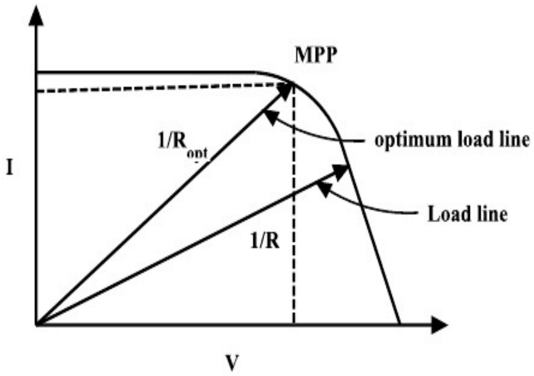

Figure 2: Concept of maximum power point tracking [8]

Different MPPT Techniques

There are different techniques used to track the maximum power point. MPPT techniques are categorised as direct and indirect methods. Direct method of MPPT algorithms is independent from prior knowledge of PV modules characteristics. The MPPT algorithms that include in this category are perturb and observe method (P&O), incremental conductance method (INC) and Fuzzy logic method.

Perturb and Observe Method

In the P&O method, the perturbation is applied either in the reference voltage or in the reference current signal of the solar PV. The flow chart of the conventional P&O method is shown in Figure3. In this flow chart, Y is shown as the reference signal. It could be either solar PV voltage or current.

The main aim is to achieve the MPP. To achieve this, the system operating point is changed by applying a small perturbation (ΔY) in solar PV reference signal. After each perturbation, the power output is measured. If the value of power measured is more than the previous value, then the perturbation in reference signal is continued in the same direction. At any point, if the new value of solar PV power is measured less than the previous one, then the perturbation is applied in the opposite direction. This process is continued till MPP is achieved. The reference signal is either incremented or decremented periodically, comparing the power obtained in the present cycle [9].

The reference signal is considered as PV voltage in this work. Table 1 presents the summary of the P&O MPPT method. The main advantage of this technique is simple and easily to implement. But the disadvantage of this method is the operating point is highly oscillated around the MPP point and not fixed on the exact MPP. The literature review reveals that with increase in the step size, the oscillations around the MPP will be more and dynamic in nature. With the reduction in step size, the convergence speed will be very less [9].

Table 1: Summary of the Perturb and Observe MPPT method

Perturbation	Change in power	Next perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

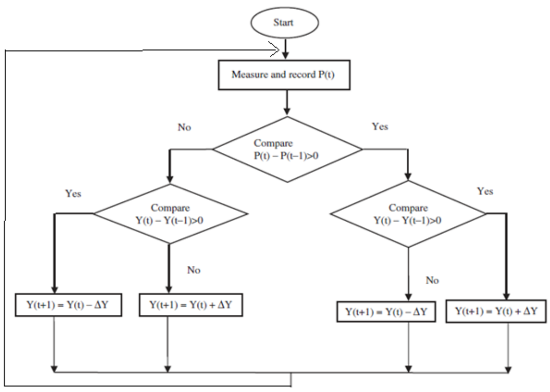

Figure 3: Flowchart of conventional Perturb and Observe MPPT method [9]

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ISSN: 2319-4863

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Incremental Conductance

The incremental conductance algorithm employs the fact that the derivative of PV power versus voltage curve is 0 at MPP, positive on the left side and negative on the right side of the MPP. The main idea is to compare the incremental conductance $\frac{\Delta I}{\Delta V}$ to the instantaneous conductance $\frac{I}{V}$. Depending on the result, the PV operating voltage is either increased, or decreased until the MPP is reached [5].

$$\frac{dP}{dV} = 0 \quad \text{at MPP} \qquad (1)$$
$$\frac{dP}{dV} > 0 \quad \text{left of MPP} \qquad (2)$$
$$\frac{dP}{dV} < 0 \quad \text{right of MPP} \qquad (3)$$

The power derivative can be also written as [5]:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \qquad (4)$$

So the above set of equations can be rewritten as:

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \quad \text{at MPP} \qquad (5)$$
$$\frac{\Delta I}{\Delta V} > \frac{-I}{V} \quad \text{left of MPP} \qquad (6)$$
$$\frac{\Delta I}{\Delta V} < \frac{-I}{V} \quad \text{right of MPP} \qquad (7)$$

At maximum power point the conductance and incremental conductance are equal but opposite sign. In the above algorithm, if it is found that $\frac{dP}{dV} = 0$ is met, then the algorithm has found the MPP point, but usually the algorithm iterates around $\frac{dP}{dV} = 0$.

The main advantage of this method is that, it is compatible with rapidly changing in solar radiation, and it has less oscillation around MPP in comparison with P&O. The disadvantage of this algorithm is the controller become more complex.

The flow chart of the Incremental Conductance method is shown in Figure 4.

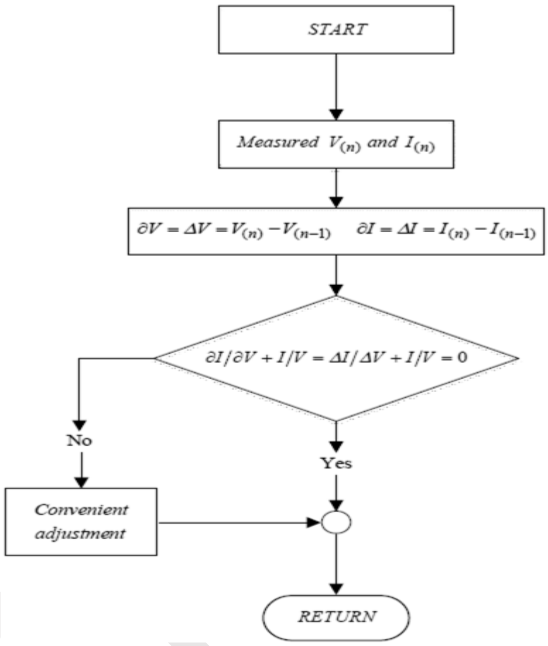

Figure 4: Flowchart of Incremental Conductance Method [10]

Fuzzy Logic MPPT

MPPT algorithms maximize power output by gradually increasing or decreasing the duty ratio of the power converter according to the PV cell output power versus the voltage curve or the current versus voltage curve. Commonly used MPPT techniques include the Perturb and Observe method and the Incremental Conductance method, both methods using fixed step size for the increment of the duty ratio command. If the step size is too small, the tracking process would be slowed. If the step size is too large, then the system may fluctuate about the maximum power point (MPP) In order to automatically adjust step sizes, variable step sizing algorithms based on artificial intelligent techniques such as Fuzzy logic system were assessed.

Mamdani-Type Fuzzy Inference Process
In Fuzzy logical operations, AND, OR, and NOT operators of Boolean are defined as the minimum, maximum, and complement, when they are defined this way, they are called the Zadeh operators. So for the Fuzzy variables A and B, logical AND is expressed by function min, so the statement A AND B is equal to min (A, B). Logical OR is defined by function max, thus A OR B becomes equivalent to max (A, B).
Mamdani-type Fuzzy inference process consists of fuzzification, then applying implication method and

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ISSN: 2319-4863

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defuzzification. During fuzzification membership function values are assigned to input linguistic variables. It maps each point in the input space to a membership value in a closed unit interval [0, 1]. Membership function values are assigned to the linguistic variables, using three Fuzzy subsets: NB (negative big), ZE (zero), and PB (positive big).

Fuzzy inference is the process of mapping the given input variables to an output space via Fuzzy logic based deducing mechanism which is comprised by If-Then rules, membership functions and Fuzzy logical operations. In this study the input of FLC is change in PV power (ΔP), the membership function and the Fuzzy rules are shown in Figure 5.

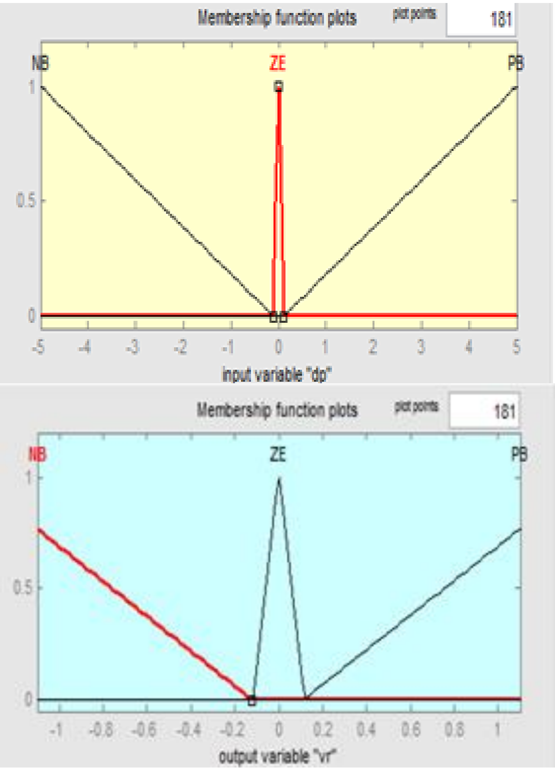

Figure 5: Membership Function Plots for input and output variables

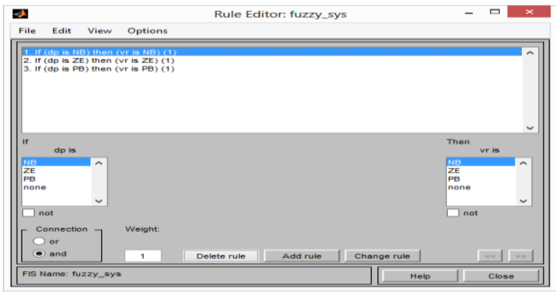

Figure 6: Fuzzy Rules for input and output variables

III. Proposed Methodology

Consider a PV module supplying a resistive load as shown in Figure 7. The load curve is accomplished by the Ohm's law, while the generation curve is related to the photovoltaic I-V curve. Both curves are represented indicating the desired behaviour is shown in Figure 8.

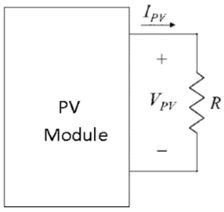

Figure 7: PV module supplying a resistive load

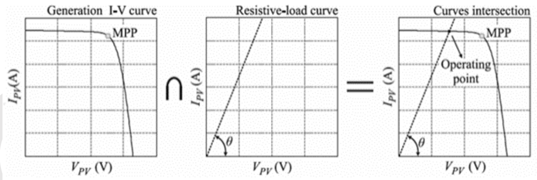

Figure 8: Definition of the system operating point by the I-V and load curves intersection [11]

MPPT System

Now as seen the operating point is different from maximum power point, so in order to ensure that system always operating on the MPP, the load curve should be modified, if a DC-DC converter is interposed between the PV module and the load, it is possible to control the converter duty cycle in order to emulate a variable load from the PV terminals point of view, even when a fixed load is employed. The arrangement is shown in Figure 9, composed by a PV module, DC-DC converter and a load [11].

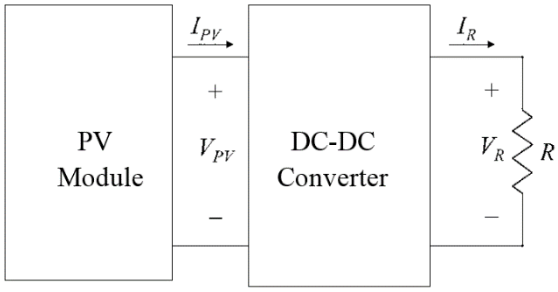

Figure 9: Maximum Power Point tracking system

DC-DC Converter Selection Criteria

When a resistive load is connected to the DC-DC converter as shown in Figure 9, the relationship between output voltage and current according to Ohm's law given by following equation.

$$V_R = I_R R \quad (8)$$

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ISSN: 2319-4863

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Taking into account a DC-DC converters static gain G, the input system variables (V_{PV} and I_{PV}) can strictly be associated to the output ones (V_R and I_R), as shown

$$G = \frac{V_R}{V_{PV}} \quad (9)$$

$$G = \frac{I_{PV}}{I_R} \quad (10)$$

By rearranging Equation (9) and (10), the new equation is given as:

$$\frac{V_{PV}}{I_{PV}} = \frac{R}{G^2} \quad (11)$$

The term $\frac{V_{PV}}{I_{PV}}$ describes the effective resistance R_{eff} obtained from the PV module terminals.

When plotted on I-V plan, Equation (11) results in a straight line whose inclination angle θ is given by:

$$\theta = tan^{-1}\frac{G^2}{R} \quad (12)$$

Table 2 presents static gain, as a function of the duty cycle D, for the DC-DC converter in continuous conduction mode (CCM). Applying the results from Table 2 in Equation (12), it is possible to describe the effective inclination angle θ, for each converter, as a variable dependent on the duty cycle D.

Table 2: Static gain for DC-DC Converters

DC-DC Converter	Static Gain
Buck Converter	$G = D$
Boost Converter	$G = \frac{1}{1-D}$
Buck-Boost Converter	$G = \frac{D}{1-D}$

Since the duty cycle is limited between 0 and 1, the effective inclination angle becomes restricted into a range whose extremes are dependent on the considered DC-DC converter. For instance, when buck converter is taken into account, for null duty cycle [11].

$$\theta|_{D=0} = tan^{-1}\frac{0^2}{R} = 0 \quad (13)$$

Thereby, if the duty cycle is set on its high value, D=1, Equation (12) can be written as:

$$\theta|_{D=1} = tan^{-1}\frac{1}{R} \quad (14)$$

In other to extend the presented analysis for further converters, a similar procedure can be applied, resulting at Table 3 and Figure 10.

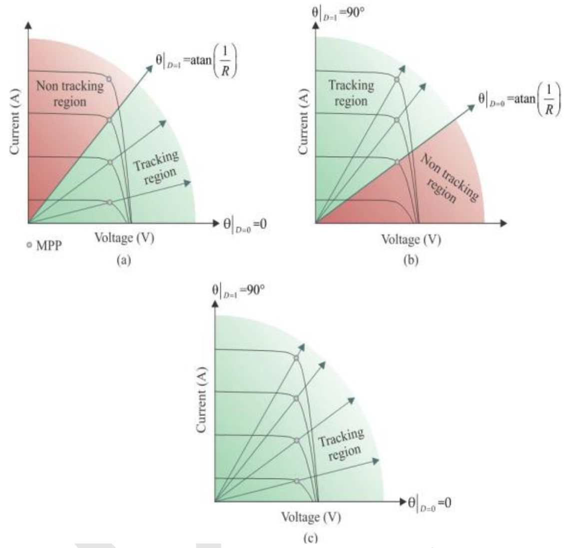

Figure 10: Tracking and non-tracking regions for: (a) Buck Converter, (b) Boost Converter and (c) Buck-Boost Converters [12]

Hence, it is found that amongst three converters buck- boost converter is the best choice as it tracks power for θ=0° to θ=90° in I-V curve.

Table 3: Minimum and maximum effective load inclination for DC-DC Converters

DC-DC Converter	Minimum effective load inclination angle	Maximum effective load inclination angle
Buck Converter	$\theta|_{D=0} = tan^{-1}\frac{0^2}{R} = 0$	$\theta|_{D=1} = tan^{-1}\frac{1}{R}$
Boost Converter	$\theta|_{D=0} = tan^{-1}\frac{1}{R}$	$\theta|_{D=1} = 90°$
Buck-Boost Converter	$\theta|_{D=0} = tan^{-1}\frac{0^2}{R} = 0$	$\theta|_{D=1} = 90°$

From Table 3 it is noticed that effective load inclination angle defines an area on the I-V plan where the maximum power can be tracked. For a better understanding, Table 3 is graphically explained through Figure 10, where two distinct regions are identified: tracking and non-tracking regions.

The tracking region refers to the area on the I-V plan in which the DC-DC converter is able to emulate a proper effective load curve in order to intercept the I-V curve exactly on the MPP, ensuring the maximum power transfer. When solar radiation change, the maximum power point is relocated on the I-V plan, thus, the effective load inclination angle must also be modified in order to re-establish the maximum power transfer [12].

Buck-Boost Converter & Operation

The general configuration of buck-boost converter is shown in Figure 11. It consists of a dc input voltage

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source V_1, inductor L, controlled switch Q, diode D, filter capacitor C, and the load resistance R. Buck-Boost converter will function as buck (step-down) converter if duty ratio is less than 0.5 and as boost (step –up) converter if duty ratio is greater than 0.

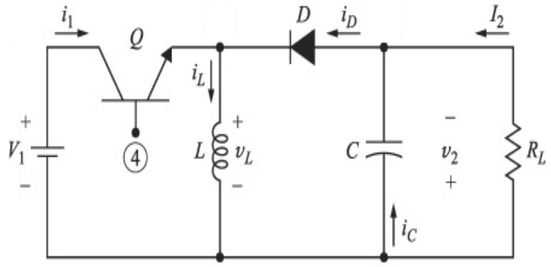

Figure 11: Configuration of a Buck Boost Converter [13]

The circuit operation can be divided into two modes:

Mode1

During mode 1, the switch Q is turned on and the diode D is reversed biased. In mode 1 the input current (i_1), which rises, flows through inductor L and switch S_1 [12].

Mode 2

In mode 2, the switch Q is off and the current, which was flowing through the inductor, would flow through L, C, D and load. In this mode the energy stored in the inductor (L) is transferred to the load and the inductor current (i_L) falls until the switch Q is turned on again in the next cycle. Over complete cycle the average value of voltage across inductor and average current through capacitor is zero [12]. The waveforms for the steady-state voltage and current are shown in Figure 12.

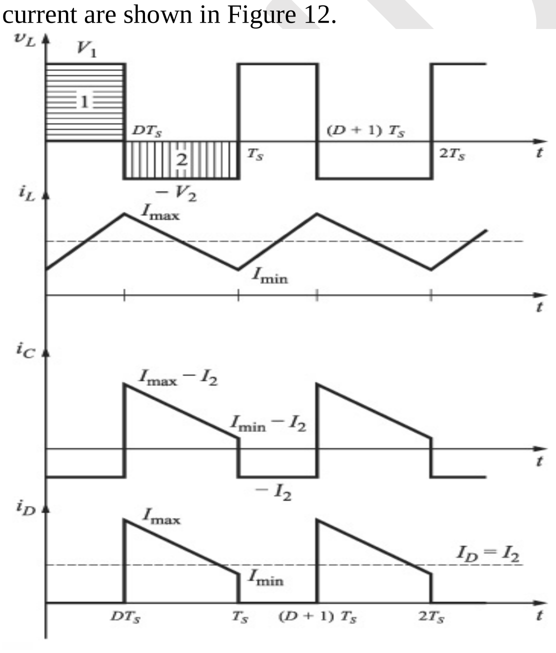

Figure 12: Current and voltage waveforms of Buck Boost Converter [13]

Based on the relation (volt-second balance) that average voltage across inductor over a complete cycle is zero, the relation between input and output voltage for Buck-Boost converter shown in Figure 11 is:

$$V_2 = V_1 \frac{D}{1-D} \qquad (15)$$

Where,

D is duty ratio of switch varies between 0 & 1.

V_2 is output voltage across load resistance R_L.

V_1 is input source voltage.

Control of DC-DC Converter

The output of DC-DC converters is controlled by varying ON-OFF time of switch with constant frequency. MPPT will generate a signal which is compared with constant frequency ramp signal, a square wave is generated after it and it is fed to DC-DC Converter. The task of the MPPT algorithm is just to calculate the reference voltage V_{ref} towards which the PV operating voltage should move next for obtaining maximum power output. This process is repeated periodically with a slower rate of around 1-10 samples per second. The pulse width modulation is carried in the PWM block at a considerably faster switching frequency. The controller works towards minimizing the error between V_{ref} and the measured voltage by varying the duty cycle through the switch.

IV. Simulation And Results

The performance of proposed algorithms has been studied by means of MATLAB / SIMULINK.

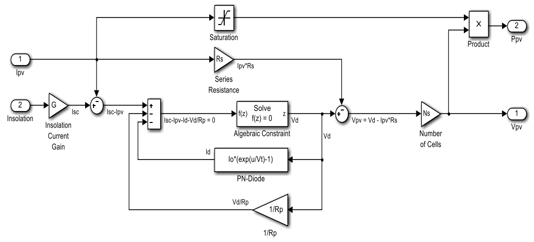

Figure 13: Simulink model of PV Array

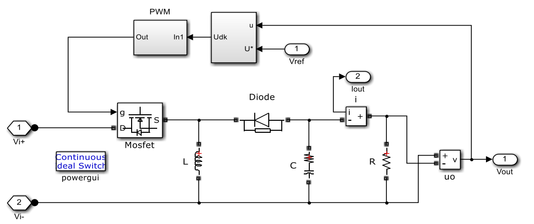

Figure 14: Simulink model of Buck-Boost Converter

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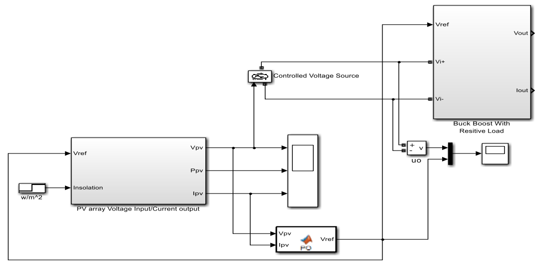

Figure 15: Simulink model of MPPT system with PV Array & Buck-Boost Converter

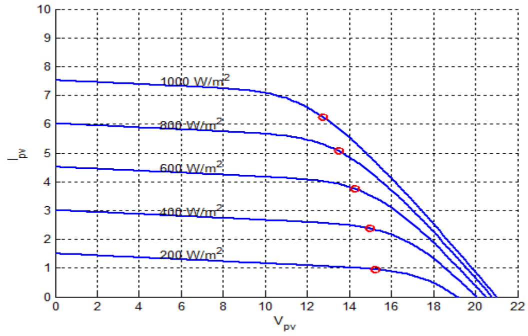

Figure 16: IPV-VPV Characteristics for different radiation values

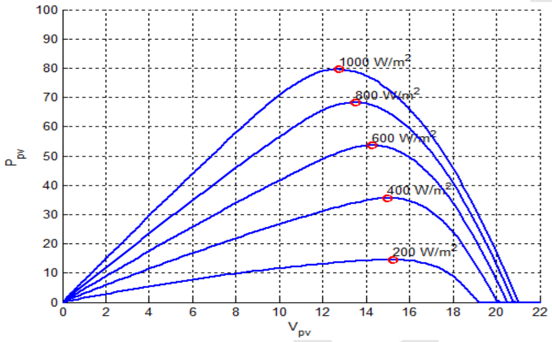

Figure 17: PPV-VPV Characteristics for different radiation values

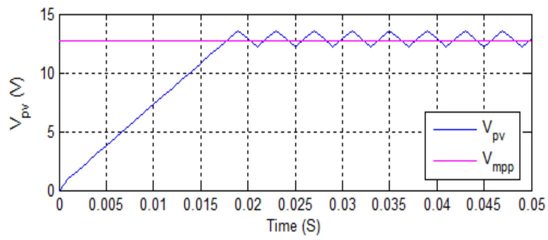

Figure 18: PV Voltage versus time curve generated by Perturb and Observe algorithm for step size of 0.7 and radiation of 1000 W/m^2

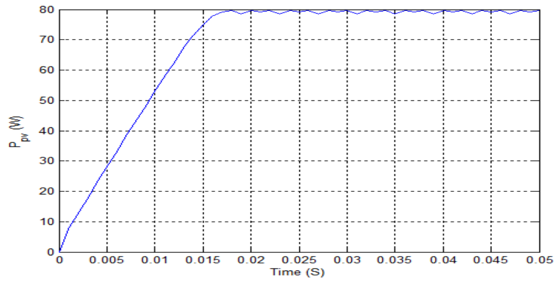

Figure 19: PV Power versus time curve generated by Perturb and Observe algorithm for step size of 0.7 and radiation of 1000 W/m^2

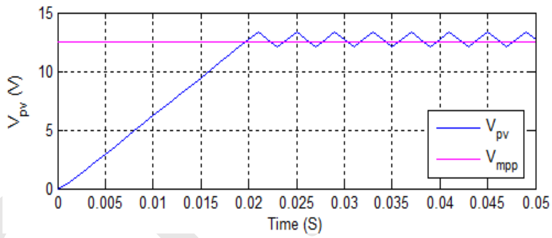

Figure 20: PV Voltage versus time curve generated by Incremental Conductance algorithm for step size of 0.7 and radiation of 1000 W/m^2.

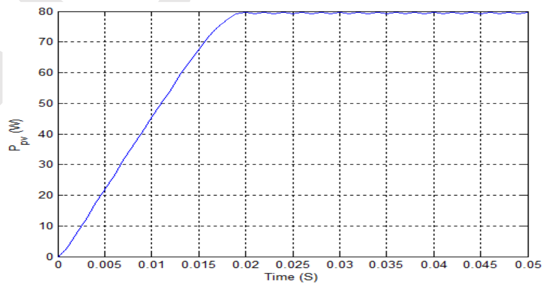

Figure 21: PV Power versus time curve generated by Incremental Conductance algorithm for step size of 0.7 and radiation of 1000 W/m^2

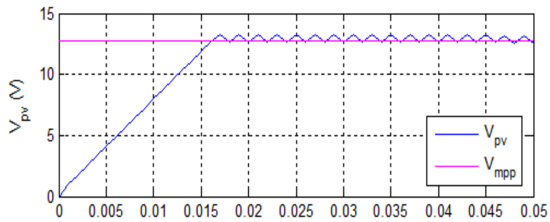

Figure 22: PV Voltage versus time curve generated by Fuzzy Logic Control for radiation of 1000W/m^2

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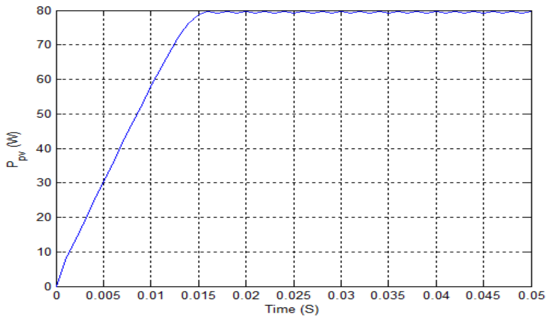

Figure 23: PV Power versus time curve generated by Fuzzy Logic Control for radiation of 1000 W/m^2

Table 4: Comparative Analysis of different MPPT techniques

Sr. No.	MPPT Technique	Variation in Power at maximum power point	Variation in Voltage at maximum power point	Ripple in Power (Watts)	Settling time (mili-second)
1.	Perturb & Observe	78.6-79.6W	12.2-13.5V	±1W	18 milli-sec
2.	Incremental Conductance	79.1-79.7W	12.1-13.4V	±0.6	20 milli-sec
3.	Fuzzy Logic Control	79.2-79.6W	12.7-13.3V	±0.4	15.7 milli-sec

V. Conclusion

From the different MPPT techniques it is investigated that P&O, INC and Fuzzy Logic Control techniques can track the maximum power point, whereas in techniques P&O and INC, one has to maintain a trade-off between settling time and power losses. Lastly, if one selects a larger step size then settling time will be reduced but the power loss at maximum power point will increase. For practical implementation, the FLC must be selected to get an outstanding performance as compared to the P&O, INC technique.

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