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Performance Analysis of the Perturb-and-Observe and Incremental Conductance MPPT under Varying Weather Conditions

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***Abstract*—Solar Photovoltaic arrays produce maximum power output and non-linear PV characteristics under maximum and uniform solar irradiance. Conventional maximum power point tracking (MPPT) charge controllers are designed to extract maximum power from SPV arrays by tracking the maximum power point (MPP) from the PV characteristics of the array. MPPT faces a major challenge to continuously track the MPP during certain environment conditions such as temperature rise, changing irradiance, partial or complete shadings, etc. In field condition, when the PV array operates under varying irradiance or partial shading condition, it becomes difficult for MPPT charge controllers to track the MPP due to multiple MPP. This paper presents a comparative study of the two most hitherto known MPPT techniques i.e. Perturb-and-Observe (P&O) and Incremental Conductance (INC) under various weather conditions such as varying irradiance and partial shading using MATLAB/SIMULINK.**

Keywords-Photovoltaic systems; varying irradiance; partial shading; maximum power point tracking (MPPT); Perturb-and-Observe (P&O); Incremental Conductance (INC)

I. INTRODUCTION

Solar energy gained an enormous popularity in India due to its abundancy, low-cost, environmental friendly, zero carbon emission and low maintenance characteristics [1]. Photovoltaic (PV) cells can easily convert the abundantly and freely available energy from sun known as solar energy into electrical energy. A PV source is basically known for its advantages like zero pollution, no moving parts and no environmental concerns [2, 3]. But, PV faces a major drawback for its ineffectiveness during non-sunshine hours, low irradiance situation and partial/ complete shading conditions. The PV system also faces another hurdle of high installation and implementation cost in gaining popularity. These drawbacks have been tackled by the PV system due to technology advancement and incentives given by the government of India. PV also faces a major challenge in its non-linear current-voltage (I~V) characteristics that result in getting a unique maximum power point (MPP) on its power-voltage (P~V) characteristics. These characteristics of PV directly depend on irradiance and temperature. The current output from PV depends on the irradiance i.e. decrease in irradiance leads to decreased current output. The voltage output of PV depends on its operating temperature i.e. with increase in temperature, voltage output decreases. In field condition, I~V and P~V characteristics of the PV source varies rapidly due to varying weather conditions. During changing irradiance and partial shading conditions, the P~V characteristics of the PV source produces more than one MPP. As a result, the maximum power point (MPP) of the system varies according to the characteristics of PV.

Considering the low energy conversion efficiency and high installation cost of PV system, the PV system must be operated at MPP so as to extract maximum power. Different methods are used in solar charge controller circuits for tracking the MPP of the PV source. In present scenario, there are more than 15 types of maximum power point tracking (MPPT) control algorithm such as constant voltage (CV) method, constant current (CC) method, open circuit voltage method, short circuit current method, perturb-and-observe (P&O) or hill climbing method, incremental conductance (INC) method, and ripple correlation approaches, etc. with different modes of implementation and operation [4, 5]. Among those, the best known and used MPPT techniques are Perturb-and-Observe (P&O) and Incremental Conductance (INC). These techniques adjust the optimal set point of the MPP to regulate the voltage of PV array. Both P&O and INC vary from each other by their complexity, sensors requirements, convergence speed, hardware implementation, cost, effectiveness, accuracy and popularity. [6]

This paper studies the effectiveness of the most hitherto known MPPT techniques i.e. perturb-and-observe (P&O) and incremental conductance (INC) under various environmental conditions such as changing irradiance and partial shading that can reduce the power output of PV using MATLAB/SIMULINK. This study has been done to determine the most effective, speed and optimal tracking algorithm during the changing weather conditions.

II. SYSTEM CONFIGURATION

A. Modelling of PV Cell

Generally, a SPV cell is a current generator consists of a diode in parallel which is represented by an equivalent circuit as shown in Figure 1.

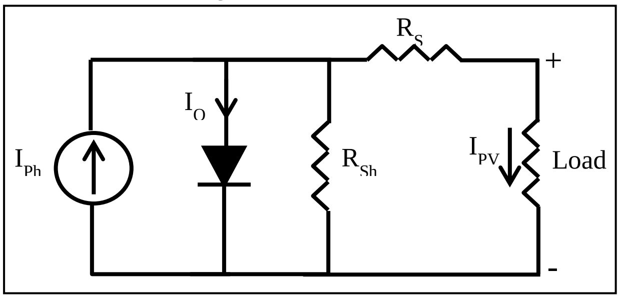


Figure 1. Equivalent circuit of a PV cell

The photo current of the cell is represented by a current source I_{Ph}. R_S and R_{Sh} are the internal series and shunt resistances respectively. Usually R_S value is very small as compared to large value of R_{Sh}, so these are neglected. PV module is designed by connecting a number of PV cells in series. A is the ideality factor. I_{PV} is the generated current. V_{PV} is the PV voltage. 'q' is the charge of electron (1.6 x 10^{-19} C).

The mathematical modeling of PV cell can be done using the given equation.

$$I_{PV} = I_{Ph} - I_o\left[\exp\left(\frac{V_{PV}+R_s I_{PV}}{A}\right)-1\right]-\left[\frac{\left(V_{pv}+I_{pv}R_s\right)}{R_{sh}}\right] \quad (1)$$

PV cells are connected in series configuration to form PV modules. Several PV modules are connected in series to form a PV string and then in parallel to form an array to deliver the desired voltage and current by the load.

B. Modelling of MPPT based Solar Charge Controller

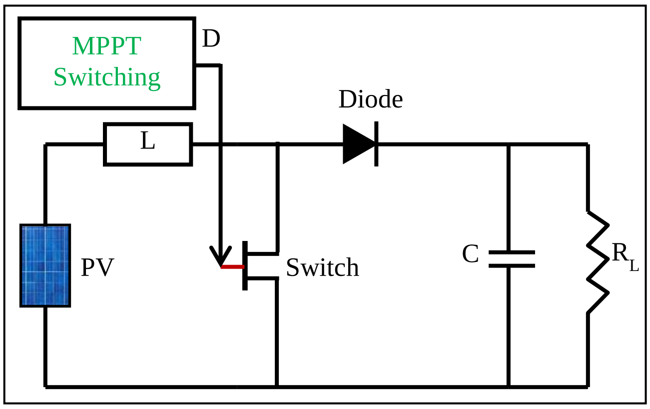


Figure 2. Equivalent Circuit of a solar charge controller (SCC)

Basically a Solar Charge Controller (SCC) consists of a boost converter and a MPPT algorithm based switching controller. The PV is connected to the input terminals and load is connected to the outer terminals of the SCC circuit. The circuit representation of PV with boost converter is shown in Figure 2. 'L' represents the inductor, 'D" is the duty cycle, C is the capacitor and R_L represents a resistive load as shown in Figure 2.

The switching of the SCC control circuit is done using MPPT algorithm to track maximum power point of the system. The schematic block representation of MPPT control circuit has been shown in Figure 3.

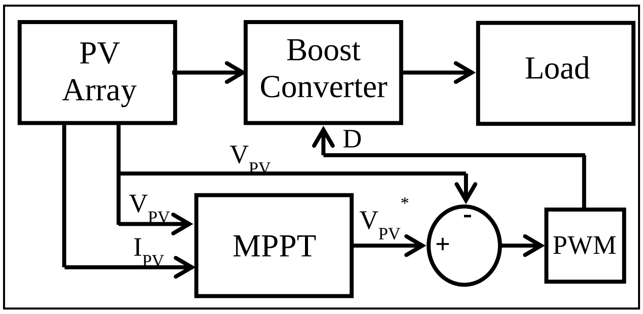


Figure 3. Control Strategy of MPPT based solar charge controller (SCC)

V_{PV} and I_{PV} are the output voltage and current of the PV array respectively which are fed to MPPT algorithm to get the reference voltage (V_{PV}*) which is compared with the previous value of V_{PV} and then fed to Pulse Width Modulation (PWM) controller to get the duty cycle (D).

C. Implementation of MPPT Algorithms

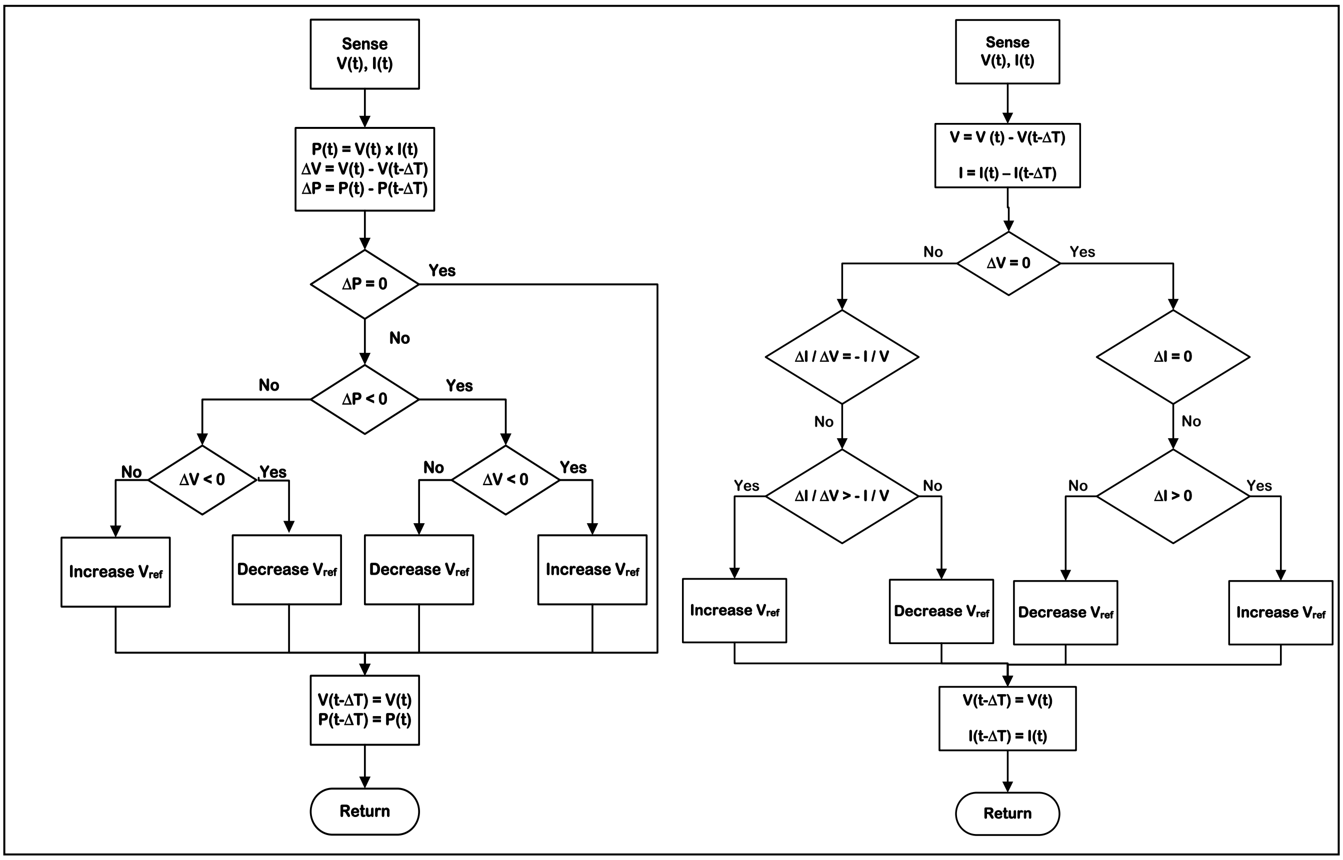
The main objective of the MPPT algorithm is to adjust the voltage of the system according to the MPP so as to track maximum power from the PV system under a specific irradiance. The commonly used MPPT techniques i.e. P&O and INC are explained in this section.

1) Perturb-and-Observe (P&O) MPPT Method

P&O is best known for its simplicity, excellent performance and ease of implementation in low cost PV systems. This technique distributes the voltage or current of the PV array and observes its effect on the P~V characteristics of the PV array to get the maximum power. In this algorithm, the previous step power is compare with the next step power of the PV array so as to adjust the voltage or current by incrementing or decrementing their values. The reference value of voltage or current is varied in this method to set the MPP. After that, the operating point of the system is moved periodically towards the MPP by either incrementing (+ve) or decrementing (-ve) the PV array voltage or current. The value of current must be changed constantly so as reduce the steady state ripple and obtain a fast dynamic response. P&O algorithm aims to maintain the MPP by perturbing the PV voltage with respective power. The change in voltage with respect to change in voltage will be zero at MPP i.e. $\partial P/\partial V = 0$. Table I represents the direction of voltage with respect to power. The similarity in sign of ΔV and ΔP leads to positive step size of +C and either signs of ΔV and ΔP lead to negative step size of –C. [9, 10]

TABLE I. TRUTH TABLE FOR P&O MPPT METHOD

Sign of ΔV	Sign of ΔP	Direction of next step
+	+	+C
-	-	+C
-	+	-C
+	-	-C



(a) (b)

Figure 4. Flowchart Representation of MPPT techniques. (a) P&O and (b) INC

Figure 4 (a) represents the flowchart for the P&O based MPPT algorithm that clearly indicates the requirement of both current and voltage sensors in the system. To improve the performance of P&O so as to track the MPP in a better way, the steps of converter duty cycle can be changed. The method in which the variation in step of converter is carried out can be termed as modified P&O method.

2) Incremental Conducatnce (INC) MPPT Method

To overcome the limitation of P&O such as steady state error, convergence speed, etc., Incremental Conductance (INC) method is proposed for MPPT. [11]

INC is cited as the best method for MPPT which is based on the principle of disturbance and observation. It works better with fast response under rapidly fluctuating solar irradiance. The INC algorithm uses the derivative of P~V characteristics (conductance) of PV array. In this method, there is a reduction in error due to fewer disturbances in operating point as compared to P&O. Figure 4 (b) represents the flowchart for INC based MPPT algorithm.

In this method, the derivative of PV array power (P) with respect to PV array voltage (V) [IC] or current (I) [Incremental Inductance-II] is set to zero. The expressions representing the INC method are:

$$\frac{\partial P}{\partial V} = \frac{\partial (V \bullet I)}{\partial V} = I \bullet \frac{\partial V}{\partial V} + V \bullet \frac{\partial I}{\partial V} = I + V\frac{\partial I}{\partial V} \quad (2)$$

$$\frac{\partial P}{\partial I} = \frac{\partial (V \bullet I)}{\partial I} = I \bullet \frac{\partial V}{\partial I} + V \bullet \frac{\partial I}{\partial I} = V + I\frac{\partial V}{\partial I} \quad (3)$$

The value instantaneous conductance and incremental conductance are compared by calculating ΔI and ΔV, and using the values of V and I from equation (2) and (3). The various modes of comparison between instantaneous and incremental conductance to track the MPP are as follows:

(i) $\partial I / \partial V = -I / V$: the operating point lies exactly on the MPP; (4)

(ii) $\partial I / \partial V > -I / V$: the operating point lies left to the MPP; (5)

(iii) $\partial I / \partial V < -I / V$: the operating point lies right to the MPP. (6)

The algorithm increases or decreases the PV array voltage according to the above comparison mentioned in equation (4-6). The method checks whether the PV array voltage is greater or less than the PV array peak power.

3) Brief Comparison among P&O and INC

P&O and INC based MPPT are analyzed in this work due to their ease of implementation, wide applicability and reduced cost. P&O and INC can be considered as the best MPPTs when good cost-benefit ratio is taken into account. Both of these techniques show better performances as compared to other conventional MPPTs. A brief comparison between P&O and INC is given in Table II.

In this paper, the two best MPPTs i.e. P&O and INC are chosen for comparison under various weather conditions such as varying irradiance and partial shading. During these conditions, the PV array current output decreases significantly that leads to decrease in power output.

TABLE II. COMPARISON AMONG P&O AND INC MPPT TECHNIQUES

Method	Advantages	Disadvantages
P&O	(i) Operation Close to MPP	(i) Complex implementation (ii) Requirement of two sensors (voltage and current) (iii) Need to choose between speed and accuracy
INC	(i) Variable Step (ii) Fast and precise technique (iii) Accurate	(i) Requirement of two sensors (voltage and current) (ii) Complex implementation due to calculation of derivatives

III. SIMULATION RESULTS AND DISCUSSIONS

The specification of PV module considered for modelling in MATLAB/ SIMULINK is given in Table III. The PV source is modelled by connecting five reference PV modules in series to form a string. Three such strings are connected in parallel to get the desired output voltage and current ratings. The comparison of P&O and INC is carried out using a dc-dc boost converter operating in continuous current mode (CCM). The parameters considered for design of the boost converter is given in Table IV. The boost converter is responsible for performing the MPPT operation when connected to PV source and load. The MPPTs are compared using four different environmental conditions i.e. constant irradiance, fluctuating irradiance, rapid fluctuating irradiance and partial shading condition.

TABLE III. SPECIFICATION OF SUNPOWER 200W PV MODULE AT STC

Parameter	Value
Maximum Power (P_M)	200 W_P
Maximum Voltage (V_M)	40 V
Maximum Current (I_M)	05 A
Open Circuit Voltage (V_{OC})	47.8 V
Short Circuit Current (I_{SC})	5.40 A

TABLE IV. DESIGN SPECIFICATION OF BOOST CONVERTER

Parameter	Value
Maximum Power (P_{Max})	3.6 KW
Inductor (L)	0.01 H
Capacitor (C)	2 mF
Load Resistance (R_L)	20 Ω
Dc-link Capacitor (C_{dc})	2 mF

A. *Under Constant Irradiance (800 W/m^2)*

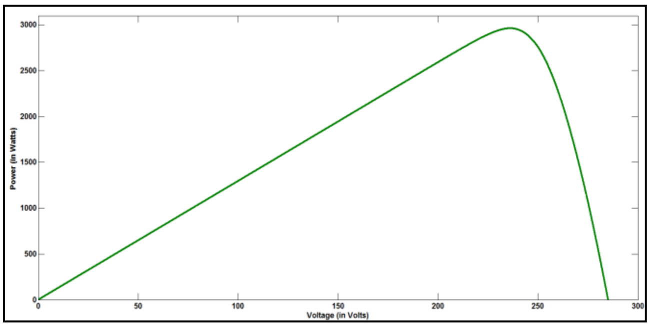


Figure 5. PV characteristics of the system under a constant irradiance of 800 W/m^2

The P~V characteristics of the system a under constant irradiance of 800 W/m^2 is shown in Figure 5. During this condition, the P~V curve have only one MPP. The simulation time of the model is kept for 2 seconds. Table V represents irradiance value w.r.t. to simulation time.

TABLE V. VALUE OF IRRADIANCE W.R.T. SIMULATION TIME

Time (in secs)	Irradiance (in W/m^2)
0-2	800

The performance of P&O and INC is studied and shown in Figure 6.

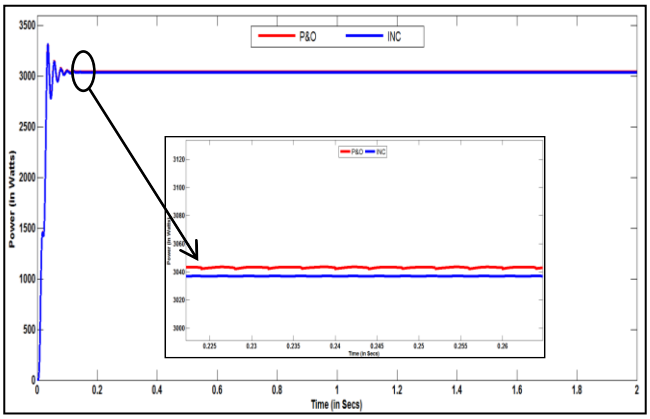


Figure 6. Performance of P&O and INC under a constant irradiance of 800 W/m^2

In this case, the maximum power tracked by P&O is found to be 3043 W whereas INC tracked 3037 W. This indicates that P&O tracked maximum power as compared to INC as shown in Figure 6. But, it has been found that INC took lesser time (0.134 secs) to track the maximum power with greater accuracy than P&O (0.165 secs). Figure 6 shows that INC delivered a lower but constant power as compared to P&O. Table VI represents the power tracked by both the MPPTs w.r.t. their time and irradiance.

TABLE VI. POWER OUTPUT W.R.T. TIME AND IRRADIANCE BY MPPTS

Irradiance (in W/m^2)	MPP tracked (in W)		Tracking Time (in Secs)	
	P&O	INC	P&O	INC
800	3043	3037	0.165	0.134

B. *Under Fluctuating Irradiance*

In this case, the irradiance of the PV source is varied respect to time as shown in Table VII.

TABLE VII. VALUE OF IRRADIANCE W.R.T. SIMULATION TIME

Time (in secs)	Irradiance (in W/m^2)
0 - 1	800
1 - 1.5	600
1.5- 2	400

The P~V characteristics of the system under this condition is shown in Figure 7. It has been found that the P~V curve got more than one MPP.

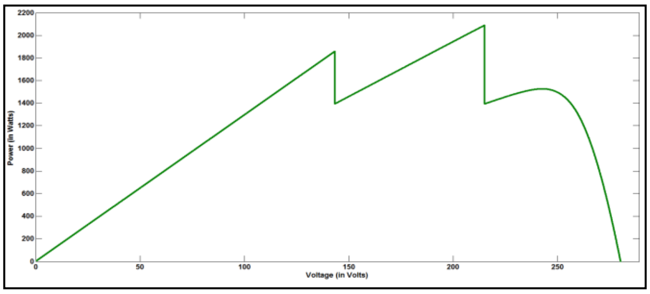


Figure 7. PV characteristics of the system under fluctuating irradiance

It has been found that at 800 W/m^2, P&O tracked 3043W (at 0.17s) whereas INC tracked 3037 W (at 0.15s). Similarly, under 600 W/m^2, P&O tracked 2845W (at 1.12s) as compared to INC i.e. 2839W (at 1.09s). At 400 W/m^2, P&O tracked 2592 W (at 1.6s) while INC tracked 2587W (at 1.58s). So, it indicates that P&O can track maximum power as compared to INC. Figure 8 represents the performance of P&O and INC during this case.

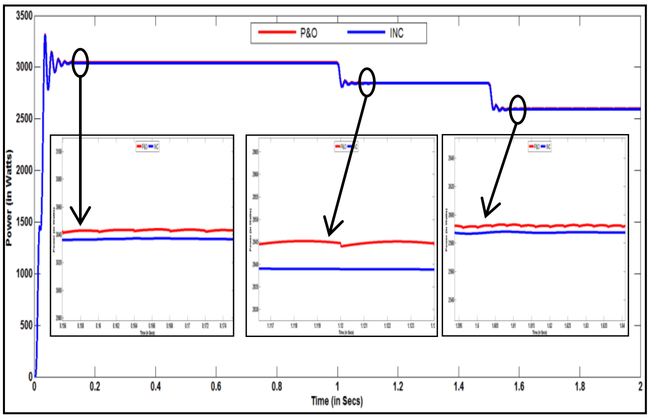


Figure 8. Performance of P&O and INC during fluctuating irradiance conditions

But, when tracking time and accuracy is taken into consideration, the time taken by INC to track MPP is less with more accuracy as compared to P&O. Table VIII represents the power tracked by P&O and INC w.r.t. their tracking time and irradiance.

TABLE VIII. POWER OUTPUT W.R.T. TIME AND IRRADIANCE BY MPPTS

Irradiance (in W/m^2)	MPP tracked (in W)		Tracking Time (in Secs)	
	P&O	INC	P&O	INC
800	3043	3037	0.17	0.15
600	2845	2839	1.12	1.09
400	2592	2587	1.6	1.58

C. Under Rapid Fluctuating Irradiance

TABLE IX. VALUE OF IRRADIANCE W.R.T. SIMULATION TIME

Time (in secs)	**Irradiance (in W/m^2)**
0 – 0.5	0
0.5 - 1	200
1 – 1.5	600
1.5 – 1.75	400
1.75 - 2	500

In this case, the irradiance of the PV system is increased and decreased rapidly with respect to time as given in Table IX. The P~V characteristics of the system during this case is shown in Figure 9 than represents the presence of more than one MPP in the curve.

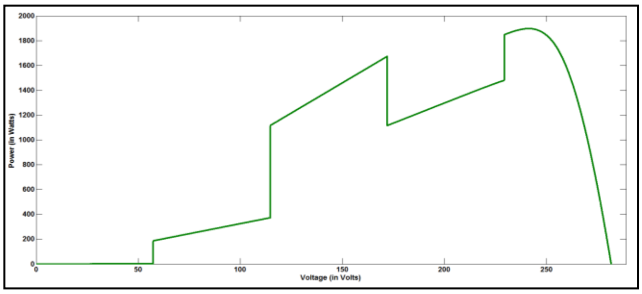


Figure 9. PV curve of the system under rapid fluctuating irradiance

During this condition, it has been found that P&O tracked the maximum power under every irradiance level as compared to INC. But, when accuracy and speed taken into account, INC excels in performance as compared to P&O. Table X represents the power tracked by P&O and INC w.r.t. their tracking time and irradiance.

TABLE X. POWER OUTPUT W.R.T. TIME AND IRRADIANCE BY MPPTS

Irradiance (in W/m^2)	MPP tracked (in W)		Tracking Time (in Secs)	
	P&O	INC	P&O	INC
0	0	0	0	0
200	1689	1695	0.84	0.81
600	2845	2839	1.12	1.10
400	2592	2587	1.60	1.57
500	2739	2734	1.847	1.81

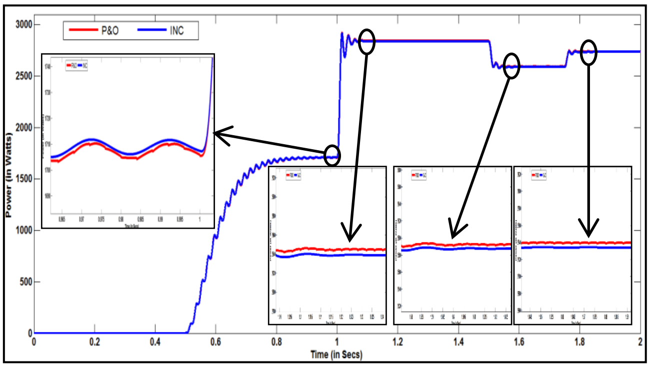


Figure 10. Performance of P&O and INC during rapid fluctuating irradiance conditions

Figure 10 represents the performance of P&O and INC during rapid fluctuating irradiance condition. The figure clearly indicates that INC tracked the maximum power with less time under low irradiance condition (200 W/m^2). During other irradiance case, P&O tracked maximum power as compared to INC.

D. Under Partial Shading Condition

During this condition, 25% of the PV array is subjected to shading to study the effect of power reduction in P&O and INC. Partial shading results in decrease of current output from the PV array therefore reducing the power output. The irradiance of unshaded and shaded PV modules is set at 800W/m^2 and 100 W/m^2. Figure 11 represents the P~V characteristics of the PV array during partial shading condition that indicates presence of more than one MPP.

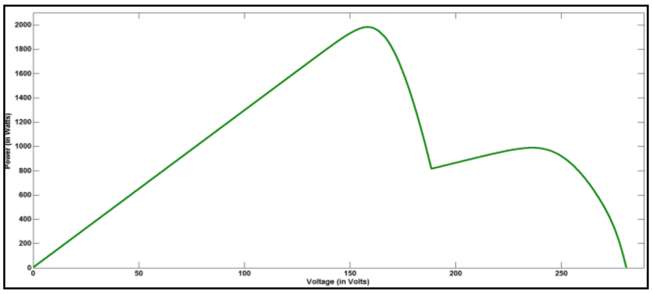


Figure 11. PV curve of the system under partial shading condition

During this condition, P&O tracked more power i.e. 2354W as compared to INC (2349W). But, INC tracked the maximum power in very less time (0.165s) as compared to P&O (0.154s). The performance of both the MPPTs during 25% partial shading condition is shown in Figure 12 which clearly indicates that the power graph of P&O contains more distortion as compared to power curve of INC. Table XI represents the power tracked by P&O and INC w.r.t. their tracking time and irradiance.

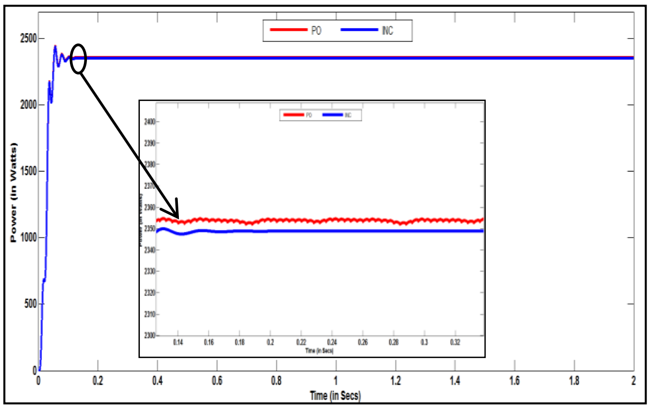


Figure 12. Performance of P&O and INC during rapid fluctuating irradiance conditions

TABLE XI. POWER OUTPUT W.R.T. TIME AND IRRADIANCE BY MPPTS

Irradiance (in W/m^2)	MPP tracked (in W)		Tracking Time (in Secs)	
	P&O	INC	P&O	INC
800	2354	2349	0.163	0.154

IV. CONCLUSION

In this study, the comparative analysis of the most hitherto known MPPT techniques i.e. P&O and INC has been done using MATLAB/SIMULINK. The performance of both the techniques has been studied under four different conditions i.e. constant irradiance, fluctuating irradiance, rapid fluctuating irradiance and partial shading. In all the cases, P&O tracked maximum power from the PV array as compared to INC. But under low irradiance level, INC tracked maximum power as compared to P&O. But when the tracking time and accuracy is taken into account, INC excels in performance over P&O. Though INC tracked slightly lower power but, its speed and accuracy excels over P&O.

So, both P&O and INC can be implemented in field depending on various field conditions such as irradiance level, PV array location, partial shading, etc.

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