

An Incremental Conductance Based Maximum Power Point Tracking for a PV Array Operating under Nonuniform Irradiance

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Abstract

Recently, the importance of exploring the plausibility of renewable energy has been progressively increased, not only because of concerns over the shortage of current fossil fuels but also the consideration of sustainable development and the negative environmental impact caused by large scale use of fossil fuels. Among renewable sources, solar energy seems to be one of the promising energy sources for widespread application. Due to its inherent intermittency and fluctuation, one of the important research interests is to harness the maximum power possible from the solar energy falling on a panel. Maximum power point tracking (MPPT) is a very important necessity in a system of energy conversion from a renewable energy source. Many research papers have been produced with various schemes over past decades for the MPPT in photovoltaic (PV) system. This paper inspires its motivation from the fact that the keen study of these existing techniques reveals that there is still quite a need for an absolutely generic and yet very simple MPPT controller which should have all the following traits: total independence from system's parameters, ability to reach the global maxima in minimal possible steps, the correct sense of tracking direction despite the abrupt atmospheric or parametrical changes, and finally having a very cost-effective and energy efficient hardware with the complexity no more than that of a minimal MPPT algorithm like Incremental Conductance. The MPPT controller presented in this paper is a successful attempt to fulfill all these requirements. It extends the MPPT techniques found in the recent research papers with some innovations in the control algorithm. The simulation results confirm that the proposed MPPT controller is very fast, very efficient, very simple and low cost as compared to the contemporary ones.

Keywords: Global peak (GP), maximum power point tracking (MPPT), partial shading, power–voltage (P –V) characteristics

I. INTRODUCTION

Decreasing cost of photovoltaic (PV) energy, and arrival of grid parity in some regions, besides environmental impact of fossil fuels, depict a promising future for the solar cells. But finding true operating point for PVs are challenging, because solar cells are inherently nonlinear devices and their performance depends on insolation level and temperature.

Maximum power point tracking (MPPT) is a technique that grid connected inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels, though optical power transmission systems can benefit from similar technology.

Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve (Fig.1). It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.

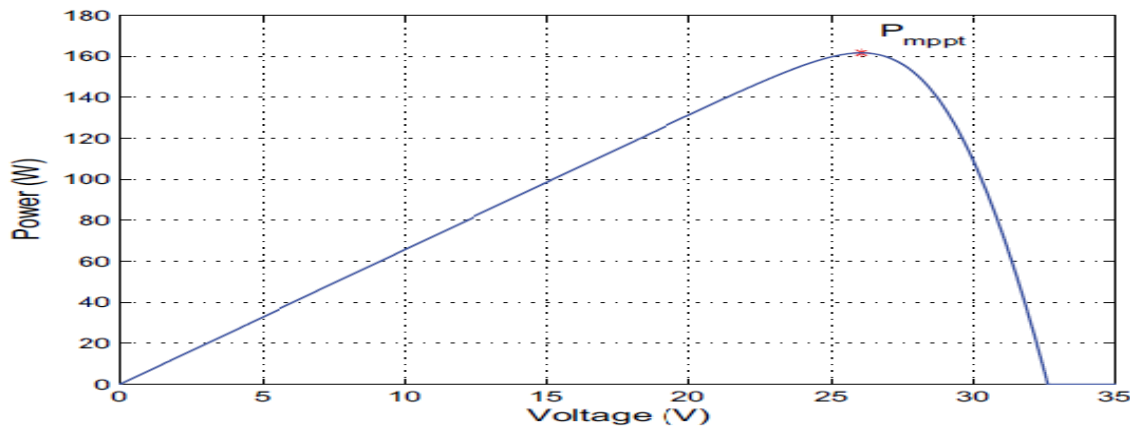


Fig. 1: Typical V-P curve of PV module

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of a PV system. As such, many MPP tracking (MPPT) methods have been developed and implemented. The methods vary in:

- 1) complexity
- 2) sensors required
- 3) convergence speed
- 4) cost, range of effectiveness
- 5) implementation hardware
- 6) popularity

They range from the almost obvious (but not necessarily ineffective) to the most creative (not necessarily most effective). Among different introduced maximum power point tracking (MPPT) techniques the Hill Climbing, Perturb and Observe (P&O) and Incremental Conductance (INC) are the most popular ones, due to ease of implementation. In fact major parts of the introduced methods are variation of these methods, which is intended to improve their performance. These methods do not get any insolation and temperature feedback and their operation are based on trial and error. They change the duty cycle in each tracking period to determine the maximum power point (MPP). So even at steady insolation they oscillate about MPP. On the other hand they confuse under rapidly changing climate condition.

However, a major drawback of the PV source is its ineffectiveness during the nights or low insolation periods or during partially shaded conditions. High initial capital cost has been another deterrent in the popularity of PV systems. These drawbacks notwithstanding, the PV systems have emerged as one of the most popular alternatives to conventional energy, thanks to the advancement in technology and favorable government policies in several countries.

Under partially shaded conditions, when the entire array does not receive uniform insolation, the P-V characteristics get more complex, displaying multiple peaks only one of which is the global peak (GP); the rest are local peaks. The presence of multiple peaks reduces the effectiveness of the existing MPP tracking (MPPT) schemes, which assume a single peak power point on the P-V characteristic. The occurrence of partially shaded conditions being quite common (e.g., due to clouds, trees, etc.), there is a need to develop Special MPPT schemes that can track the GP under these conditions.

A. Block Diagram of Solar PV System with MPPT Controller:

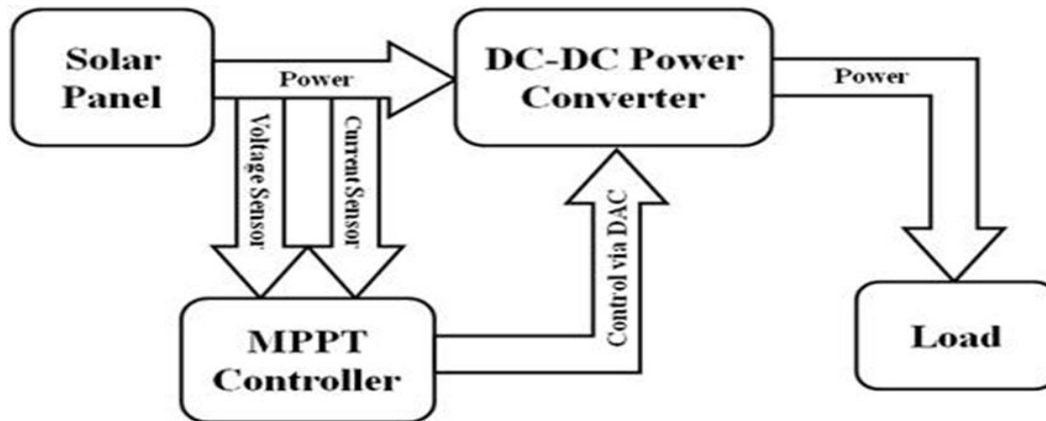


Fig. 2: Block Diagram of Solar PV System with MPPT Controller

II. REVIEW OF THE EXISTING MPPT TECHNIQUES

Figure (3) shows the characteristic power curve for a PV array. The problem considered by MPPT techniques is to automatically find the voltage V_{MPP} or current I_{MPP} at which a PV array should operate to obtain the maximum power output P_{MPP} under a given temperature and irradiance. It is noted that under partial shading conditions, in some cases it is possible to have multiple local maxima, but overall there is still only one true MPP. Most techniques respond to changes in both irradiance and temperature, but some are specifically more useful if temperature is approximately constant. Most techniques would automatically respond to changes in the array due to aging, though some are open-loop and would require periodic fine-tuning. In our context, the array will typically be connected to a power converter that can vary the current coming from the PV array.

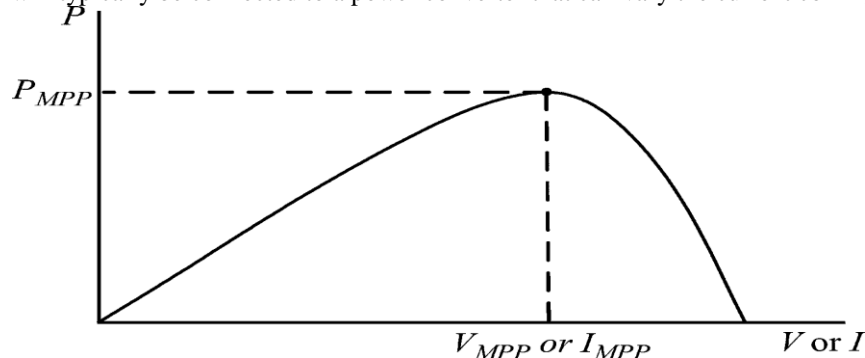


Fig. 3: Characteristic PV array power curve

A. Hill Climbing/P&O:

Hill climbing involves a perturbation in the duty ratio of the power converter, and P&O a perturbation in the operating voltage of the PV array. In the case of a PV array connected to a power converter, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Hill climbing and P&O methods are different ways to envision the same fundamental method.

From Fig. 3, it can be seen that incrementing the voltage increases the power when operating on the left of the MPP and decreases the power when on the right of the MPP and vice versa. Therefore, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed. This algorithm is summarized in Table.1

Table 1:
Summary of hill climbing and P&O algorithm

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

The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the MPPT. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP.

Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions as illustrated in Fig. 4

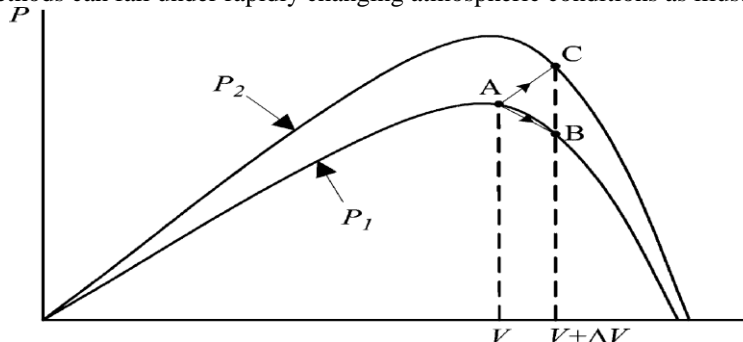


Fig. 4: Divergence of hill climbing/P&O from MPP

Starting from an operating point A, if atmospheric conditions stay approximately constant, a perturbation ΔV in the PV voltage V will bring the operating point to B and the perturbation will be reversed due to a decrease in power. However, if the irradiance increases and shifts the power curve from P1 to P2 within one sampling period, the operating point will move from A to C. This represents an increase in power and the perturbation is kept the same. Consequently, the operating point diverges from the MPP and will keep diverging if the irradiance steadily increases.

Two sensors are usually required to measure the PV array voltage and current from which power is computed. DSP or microcomputer control is more suitable for hill climbing and P&O even though discrete analog and digital circuitry can be used

B. Incremental Conductance:

The incremental conductance (IncCond) method is based on the fact that the slope of the PV array power curve (Fig. 3) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by

$$dP/dV = 0, \text{ at MPP} \quad (1)$$

$$dP/dV > 0, \text{ left of MPP} \quad (2)$$

$$dP/dV < 0, \text{ right of MPP} \quad (3)$$

Since,

$$dP/dV = d(IV)/dV = I + VdI/dV = I + V\Delta I/\Delta V \quad (4)$$

Can be rewritten as

$$\Delta I/\Delta V = -I/V, \text{ at MPP} \quad (5)$$

$$\Delta I/\Delta V > -I/V, \text{ left of MPP} \quad (6)$$

$$\Delta I/\Delta V < -I/V, \text{ right of MPP} \quad (7)$$

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$). V_{ref} is the reference voltage at which the PV array is forced to operate. At the MPP, V_{ref} equals to V_{MPP} . Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or increments V_{ref} to track the new MPP.

The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead; so there is a tradeoff. By proper control of the power converter, the initial operating point is set to match a load resistance proportional to the ratio of the open-circuit voltage (VOC) to the short-circuit current (ISC) of the PV array. This two-stage alternative also ensures that the real MPP is tracked in case of multiple local maxima.

A less obvious, but effective way of performing the Inc Cond technique is to use the instantaneous conductance and the incremental conductance to generate an error signal, "e",

We know that "e" goes to zero at the MPP. A simple proportional integral (PI) control can then be used to drive e to zero.

$$e = \frac{I}{V} + \frac{dI}{dV} \quad (8)$$

Measurements of the instantaneous PV array voltage and current require two sensors. Inc Cond method lends itself well to DSP and microcontroller control, which can easily keep track of previous values of voltage and current and make all the decisions.

C. Fractional Open-Circuit Voltage:

The near linear relationship between V_{MPP} and VOC of the PV array, under varying irradiance and temperature levels, has given rise to the fractional VOC method.

$$V_{MPP} \approx k1VOC \quad (9)$$

Where $k1$ is a constant of proportionality. Since $k1$ is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and VOC for the specific PV array at different irradiance and temperature levels. The factor $k1$ has been reported to be between 0.71 and 0.78.

Once $k1$ is known, V_{MPP} can be computed with VOC measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power. To prevent this, It use pilot cells from which VOC can be obtained. These pilot cells must be carefully chosen to closely represent the characteristics of the PV array. It is claimed that the voltage generated by pn-junction diodes is approximately 75% of VOC. This eliminates the need for measuring VOC and computing V_{MPP} . Once V_{MPP} has been approximated, a closed-loop control on the array power converter can be used to asymptotically reach this desired voltage.

The PV array technically never operates at the MPP. Depending on the application of the PV system, this can sometimes be adequate. Even if fractional VOC is not a true MPPT technique, it is very easy and cheap to implement as it does not necessarily require DSP or microcontroller control. However, points out that $k1$ is no more valid in the presence of partial shading (which causes multiple local maxima) of the PV array.

D. Fractional Short-Circuit Current:

Fractional ISC results from the fact that, under varying atmospheric conditions, IMPP is approximately linearly related to the ISC of the PV array.

$$IMPP \approx k2ISC \quad (10)$$

Where k2 is a proportionality constant. Just like in the fractional VOC technique, k2 has to be determined according to the PV array in use. The constant k2 is generally found to be between 0.78 and 0.92.

Measuring ISC during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that ISC can be measured using a current sensor. This increases the number of components and cost.

Power output is not only reduced when finding ISC but also because the MPP is never perfectly matched. A way of compensating k2 is proposed such that the MPP is better tracked while atmospheric conditions change. To guarantee proper MPPT in the presence of multiple local maxima. Most of the PV systems using fractional ISC in the literature use a DSP.

E. Fuzzy Logic Control:

Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity.

Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function. In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big).seven fuzzy levels are used, probably for more accuracy.

The inputs to a MPPT fuzzy logic controller are usually an error E and a change in error ΔE. The user has the flexibility of choosing how to compute E and ΔE. Since dP/dV vanishes at the MPP.

$$E(n) = (P(n) - P(n - 1)) / (V(n) - V(n - 1)) \quad (11)$$

$$\Delta E(n) = E(n) - E(n - 1). \quad (12)$$

Once E and ΔE are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is typically a change in duty ratio ΔD of the power converter, can be looked up in a rule base table such as Table 2

Table 2:

Fuzzy rule base table

$E \backslash \Delta E$	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

The linguistic variables assigned to ΔD for the different combinations of E and ΔE are based on the power converter being used and also on the knowledge of the user. Table II is based on a boost converter. If, for example, the operating point is far to the left of the MPP (Fig. 2.1), that is E is PB, and ΔE is ZE, then we want to largely increase the duty ratio, that is ΔD should be PB to reach the MPP in the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function as in Fig. 5. This provides an analog signal that will control the power converter to the MPP. MPPT fuzzy logic controllers have been shown to perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user or control engineer in choosing the right error computation and coming up with the rule base table.

F. Neural Network:

Along with fuzzy logic controllers came another technique of implementing MPPT—neural networks, which are also well adapted for microcontrollers.

Neural networks commonly have three layers: input, hidden, and output layers as shown in Fig. 4. The number of nodes in each layer varies and is user-dependent. The input variables can be PV array parameters like VOC and ISC, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP.

How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted. The link between nodes i and j is labeled as having a

weight of w_{ij} in Fig. 2.3. To accurately identify the MPP, the w_{ij} 's have to be carefully determined through a training process, whereby the PV array is tested over months or years and the patterns between the input(s) and output(s) of the neural network are recorded.

Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.

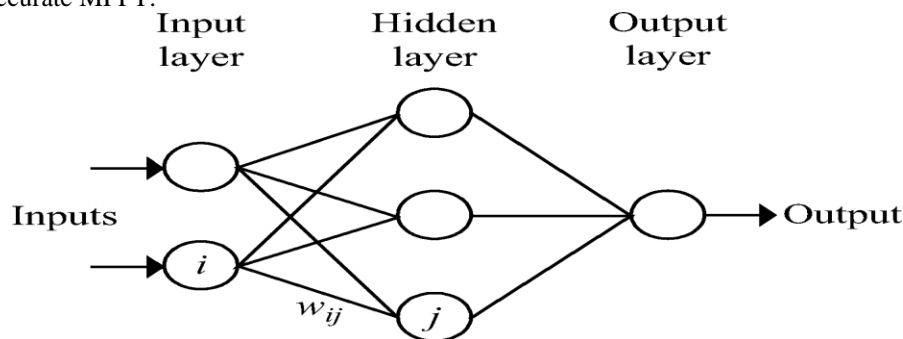


Fig. 4: Example of neural network

G. Ripple Correlation Control (RCC):

When a PV array is connected to a power converter, the switching action of the power converter imposes voltage and current ripple on the PV array. As a consequence, the PV array power is also subject to ripple. Ripple correlation control (RCC) makes use of ripple to perform MPPT. RCC correlates the time derivative of the time-varying PV array power p' with the time derivative of the time-varying PV array current i' or voltage v' to drive the power gradient to zero, thus reaching the MPP. Referring to Fig. 3, if v or i is increasing ($v' > 0$ or $i' > 0$) and p is increasing ($p' > 0$), then the operating point is below the MPP ($V < V_{MPP}$ or $I < I_{MPP}$). On the other hand, if v or i is increasing and p is decreasing ($p' < 0$), then the operating point is above the MPP ($V > V_{MPP}$ or $I > I_{MPP}$). Combining these observations, we see that $p' \cdot v'$ or $p' \cdot i'$ are positive to the left of the MPP, negative to right of the MPP, and zero at the MPP.

Simple and inexpensive analog circuits can be used to implement RCC. Experiments were performed to show that RCC accurately and quickly tracks the MPP, even under varying irradiance levels. The time taken to converge to the MPP is limited by the switching frequency of the power converter and the gain of the RCC circuit. Another advantage of RCC is that it does not require any prior information about the PV array characteristics, making its adaptation to different PV systems straightforward.

H. dP/dV or dP/dI Feedback Control:

With DSP and microcontroller being able to handle complex computations, an obvious way of performing MPPT is to compute the slope (dP/dV or dP/dI) of the PV power curve (Fig. 2.1) and feed it back to the power converter with some control to drive it to zero.

dP/dV is computed and its sign is stored for the past few cycles. Based on these signs, the duty ratio of the power converter is either incremented or decremented to reach the MPP. A dynamic step size is used to improve the transient response of the system

A linearization-based method is used to compute dP/dV . Or sampling and data conversion are used with subsequent digital division of power and voltage to approximate dP/dV . dP/dI is then integrated together with an adaptive gain to improve the transient response. the PV array voltage is periodically incremented or decremented and $\Delta P/\Delta V$ is compared to a marginal error until the MPP is reached. Convergence to the MPP was shown to occur in tens of milliseconds.

III. SIMULATION AND RESULTS

A. Simulink model of maximum MPPT under partial shaded condition:

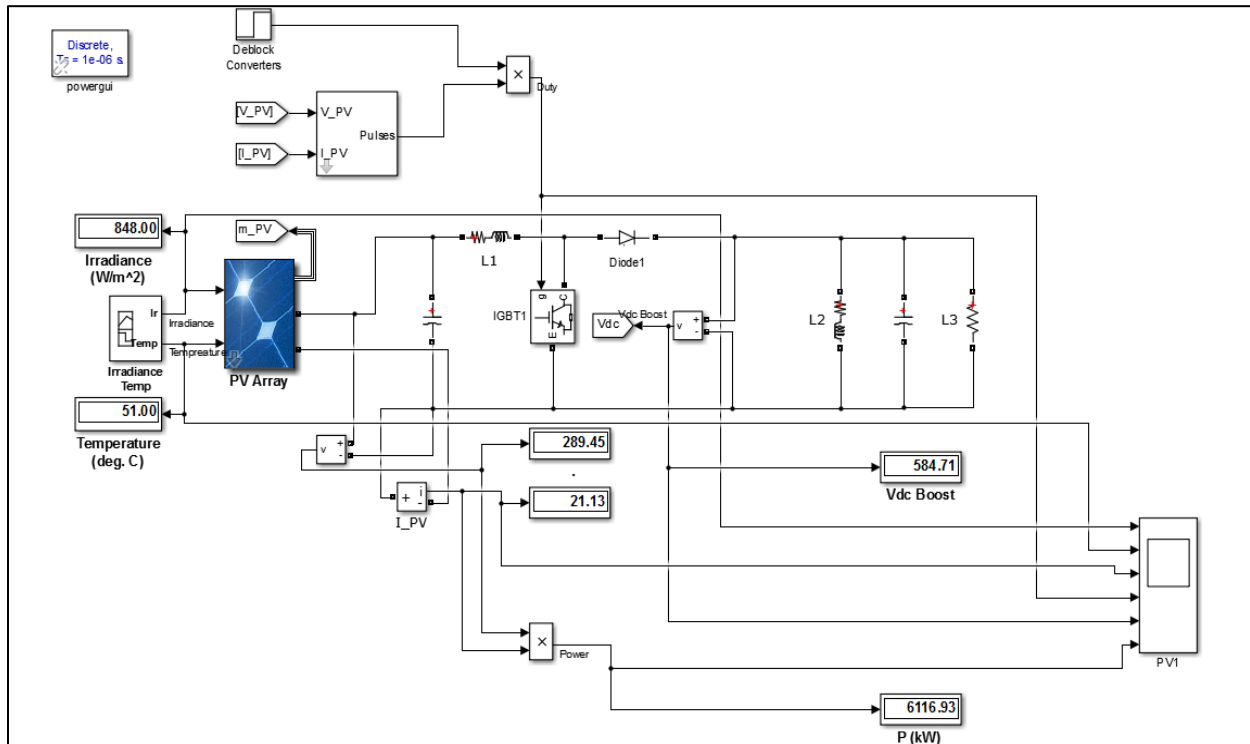


Fig. 5: Simulink model of maximum MPPT under partial shaded condition:

B. MPPT (incremental conductance) Controller:

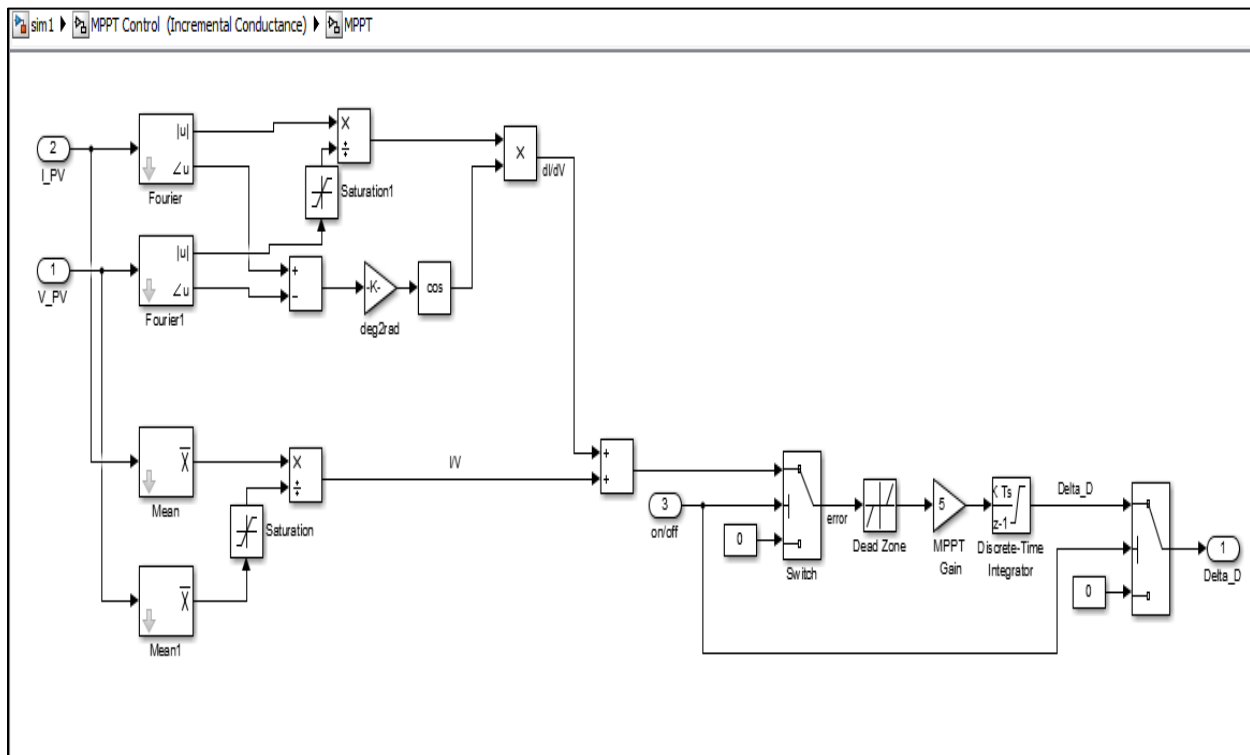
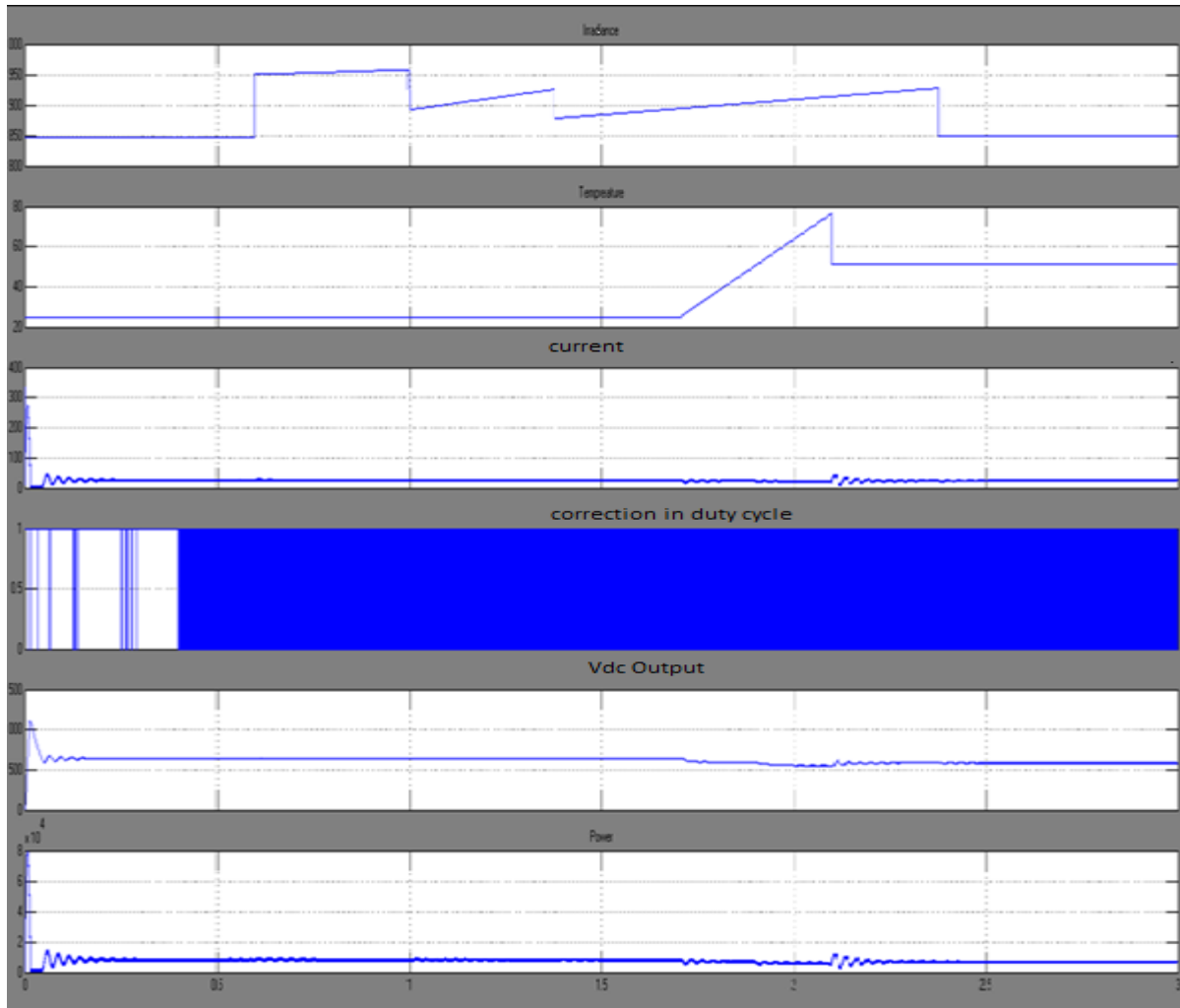


Fig. 6: MPPT(incremental conductance) Controller:

IV. RESULTS



V. CONCLUSION

Based on a comprehensive study of the I–V and P–V characteristics of a partially shaded array, several critical observations, which are useful for GP tracking, have been made, and an algorithm for tracking the GP has been presented. The salient features of the method are given as follows.

- 1) The method is simple, yet effective, to track the GP in case of partially shaded conditions. It is observed that the peaks follow a specific trend in which the power at a peak point continues to increase until it reaches the GP, and afterward, it continuously decreases.
- 2) The scheme is also effective under uniform insolation conditions.

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