Chapter 34
MATLAB/Simulink-Based Tracking of Maximum Power Point in a Generalized Photovoltaic Module by Using DC-DC Boost Converter

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1 Introduction

Today, the whole world is facing an enormous drawback of electric power shortage, which is of great concern because of the conventional methods of generating electrical energy. In India, per capita electrical energy consumption is increasing fast during recent few years; it was around 347.5 kWh in 1992, which has reached to 1075 kWh in the year 2016 and around 1122 kWh in the year 2017 [1]. In general, from the year 2017, the contribution and shares of various power sectors to meet our energy demand and financial growth of India are; coal 59%, Hydro 14%, fossil fuels 17% including 8% of gas, and nuclear 2% [2]. The high dependency of coal, oil, and fossil fuels for energy generation results in greater energy insecurities in future. With the rapidly growing requirements of energy and as per the energy forecast, the electrical energy requirement for the year 2021–2022 will be around 1750 kWh and around 2300 kWh for the 2026–2027 year [3]. Therefore to meet out this demand, energy system needs to be more efficient and sustainable with minimum environmental and ecological impacts for harvesting more energy by using Renewable Energy Sources. Among all the Renewable Energy Sources, energy generation from photovoltaic effect is considered as more effective and sustainable resource, as it uses sun as a natural energy resource, which is eco-friendly, clean, inexhaustible, abundance in nature, free and energy supplied by it consistently. A major initiative has been taken up by the Government of India to promote and increase maximum utilization of solar energy by proposing "National Solar Mission" in the year 2008, which was retitled

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Table 1 Phases and targets of (JNNSM)

Application	Phase-1 year (2010–2013)	Phase-2 year (2013–2017)	Phase-3 year (2017–2022)
Rooftop stand-alone solar plants	0.2 GW	1 GW	40 GW
Grid connected solar plants	1–2 GW	4–10 GW	60 GW
Total			100 GW

as "Jawaharlal Nehru National Solar Mission" (JNNSM) in the year 2010. The main aim of this operation is to deploy 20 Giga Watt (GW) of solar energy by the end of the year 2022. Three-phase approach is required for the execution of this operation. Different phases and goals of JNNSM are mentioned in Table 1 [4].

The energy obtained by the sun based upon the photovoltaic framework depends upon solar irradiance, cell temperature, and the voltage formed in the solar photovoltaic cells. Besides the fact that the solar photovoltaic system gives a new direction in the energy generation process, it also has some major drawbacks, which are.

1. Higher initial cost;
2. Low power conversion efficiency;
3. Electric power produced by sunlight-based photovoltaic framework is highly affected by the atmospheric conditions; variation in atmospheric conditions results in continuous change in electric power.

Figure 1 provides more clarity about the whole concept and working of how to separate most extreme power from the photovoltaic module using the MPPT system and DC-DC power converter.

As the climatic conditions for the whole duration of the day are not constant and certain parameters like solar irradiance and temperature are continuously varying all through the day, under such conditions it is difficult to find peak point where maximum power occurs. MPPT is an impedance matching and time-varying technique that interfaces changing source and possibly the fluctuating load. Among several MPPT algorithms, two more effective, fast and widely used MPPT methods

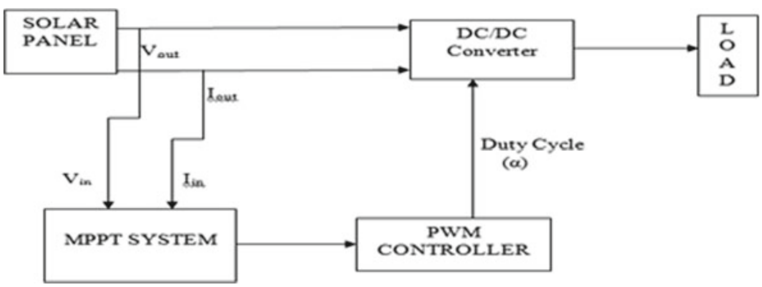

Fig. 1 Schematic diagram of maximum power tracking using DC-DC converter

that can work accurately and precisely in every single imaginable condition in order to get maximum power are.

1. Perturb and Observe Method (P&O Method),
2. Incremental Conductance Method (INC Method).

Perturb and Observe (P&O) and Incremental Conductance (INC) method are the two most optimizing and fast-tracking MPPT algorithms to track maximum power point by repeatedly updating the working voltage of the photovoltaic system. MPPT and PWM (Pulse-Width Modulation) controller helps in adjusting the duty cycle of the power DC-DC power converters with a fixed step size to transfer maximum power from the source to load.

Results obtained after simulation with conclusions are discussed in the later stage. Solar photovoltaic module, MPPT controller, and DC-DC power converter are designed and simulated using MATLAB/Simulink and simulated graphs such as I-V and P–V characteristics, graph of output power from DC-DC converter are obtained. Results of a simulated solar photovoltaic module are compared and validated with the actual results of the photovoltaic module.

2 State of the Art

Solar photovoltaic panels comprise of a number of solar photovoltaic modules which when connected with suitably designed power conditioning units such as Maximum Power Point Tracking (MPPT) controller and DC-DC converters produces maximum output power. Previous studies suggest that various investigations have been made on solar photovoltaic systems for different applications to gain as much benefits as possible from solar energy.

Some of the research works and papers presented on solar photovoltaics, simulation, and modeling of photovoltaic module in MATLAB/Simulink, interconnection of electrical load and photovoltaic module with a DC-DC power converter and implementation of Maximum Power Point Tracking (MPPT) strategies and methods are briefly conferred in this section.

Shyam. B and P. Kanakasabapathy had given an insight of various government policies, acts, plans, and strategies such as "Jawaharlal Lal Nehru Solar Mission" (JNNSM), JNNSM phases and targets initiated by Indian government agencies for country's economic growth and development. The approach toward development in the area of Smart Grid in India is additionally explained in their paper [1]. Marcelo Gradella Villalva, Jonas Rafael Gazoli, and Ernesto Ruppert Filho, had determined the three basic parameters of the photovoltaic model which are open-circuit voltage, short-circuit current, and maximum power point from the I-V characteristic curves. A photovoltaic array is designed and simulated in MATLAB/Simulink and using the simulated results mainly the output power of the photovoltaic array is matched and validated with the practically available photovoltaic array [5].

Huan-Liang Tsai, Ci-Siang Tu, and Yi-Jie Su had given an insight into how maximum power can be achieved through simulating and analyzing the proposed model by using power electronic devices [8]. Weidong Xiao, William. G. Dunford, and Antoine Capel had given a data-based approach for photovoltaic (PV) modeling. Nonlinear mathematical equations were solved for getting I-V characteristics of photovoltaic cells [9].

J. A. Cow and C. D. Manning had proposed a specific circuit-based simulated photovoltaic array model for the development of advanced solar photovoltaic (PV) conversion system [10]. S. Sheik Mohammed and D. Devaraj had presented a research study that provides a more comprehensive and detailed description on developing generalized photovoltaic module by means of simulation platform in MATLAB/Simulink and validating the simulated module with the monetarily accessible MSX 60 photovoltaic module [11].

Pandiarajan. N and Ranganath Muthu had portrayed about building up an exact power electronic circuit model necessary for designing and simulating photovoltaic integrated system [13]. Mei Shan Ngan, Chee Wei Tan have discussed two categories of MPPT algorithms, one is direct and another is indirect method [16].

Ting-Chung Yu and Yu-Cheng Lin had analyzed three most extensively used tracking methods specifically Perturb & Observe (P&O) algorithm, Incremental Conductance (INC) algorithm and Hill climbing algorithm. They described the complete development of photovoltaic system utilizing MPPT methods in MATLAB/Simulink by combining solar module and DC-DC converter with maximum power point tracking algorithms [17]. Trishan Esram and Patrick L. Chapman had given a comparative analysis of maximum power point tracking strategies on the photovoltaic array. They had discussed different methods for tracking maximum power point condition and their implementation [18].

In general, many simplifying assumptions have been made in the various proposed methods for maximum power point tracking. The aim of this paper is to develop a comprehensive computational methodology for building MATLAB/Simulink model to simulate with 'Perturb & Observe' and 'Incremental Conductance' algorithm incorporating DC-DC boost converter for getting maximum output power.

3 Proposed Methodology

The output power of the solar photovoltaic system is highly influenced by rapidly varying climatic conditions such as solar radiation and temperature. Solar photovoltaic system exhibits nonlinear I-V and P–V characteristics under different climatic conditions; operating point on P–V characteristics curve fluctuates continuously from its maximum position. The process of operating a photovoltaic array or module at or closer to maximum power point condition is known as Maximum Power Point Tracking (MPPT).

The method, which is to be applied for tracking maximum power point should be easy to implement, take lesser time to track, it should have adequate convergence speed, and price of implementation ought to be less. Various techniques have been proposed for tracking the Maximum Power Point (MPP), among these techniques, Perturb and Observe (P&O) and Incremental Conductance (INC) methods are most widely utilized techniques and are applied for tracking maximum power point.

(a) **Perturb and Observe (P&O) Method**:

P&O method is the most broadly utilized methodology for tracking maximum power due to its easy approach and very few parameters are required for the implementation of this method. The power generated by the photovoltaic module or array is perturbed, observed, and analyzed through iteration methods to locate maximum power point condition. Solar photovoltaic module or array voltage is perturbed periodically with increment and decrement in terminal voltage and comparing the output power received from photovoltaic with the previous perturbed cycle. The basis of this control algorithm is the slope (dP/dV) on the P–V characteristic curve as depicted in Fig. 2 [17].

Condition I: When the working voltage of photovoltaic module or array is perturbed in a particular direction and $dP/dV > 0$ (i.e., left aspect of the curve), then slope dP/dV is positive and direction of perturbation is toward Maximum Power Point (MPP) and P&O algorithm continues to perturb photovoltaic module or array voltage in the same direction.

Condition II: When $dP/dV < 0$, (i.e., right aspect of the curve), then slope dP/dV is negative and operating point moves far away from Maximum Power Point (MPP) and during this condition P&O algorithm reverses the direction of perturbation.

Condition III: At $dP/dV = 0$, condition of maximum power point is reached. Though maximum power can be obtained at $dP/dV = 0$, still some power is dissipated during tracking as the operating point does not remain stable and it oscillates around maximum power point. The basic operating procedure of P&O technique is given in Fig. 2.

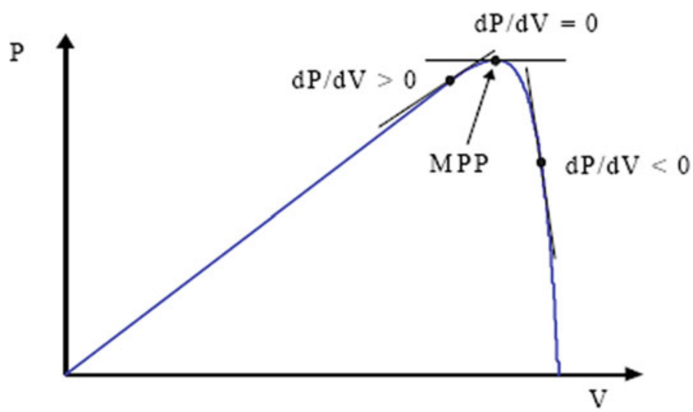

Fig. 2 Schematic diagram of P–V characteristic curve showing different positions of dP/dV

Advantages of P&O method:

1. Simple in structure and easy to implement.
2. Low computational demand.
3. Implementation cost is less.
4. Only one sensor, i.e., voltage sensor is required to sense the photovoltaic module or array voltage.

Disadvantages of P&O method:

1. Rapidly varying climatic conditions has a negative effect on the P&O method as algorithm starts tracking Maximum Power Point (MPP) in the wrong direction. The reason behind this is when atmospheric conditions changes, then simultaneously solar irradiance also changes rapidly due to which Maximum Power Point (MPP) deviates slightly from its position in either direction; P&O algorithm concludes this change as a change due to perturbation and accordingly in the successive iterations it starts perturbing in the wrong direction.
2. P&O method cannot find out exactly that when it has reached maximum power point (MPP) and operating point continuously oscillates around Maximum Power Point (MPP), which leads to some energy loss in the process.
3. Slow response speed at the event of changes in solar irradiance.

To overcome the limitations of the P&O algorithm, a new technique for tracking MPP has been established known as "Incremental Conductance methods"..

(b) **Incremental Conductance (INC) Method**:

The main concept of Incremental Conductance Method depends upon the way that slope of power curve at Maximum Power Point (MPP) is zero in the photovoltaic module; it is positive on left of Maximum Power Point (MPP) and negative on the right of the MPP, this can be explained as [18]

$$\begin{cases} \frac{dP}{dV} = 0, \text{ at MPP} \\ \frac{dP}{dV} > 0, \text{ left of MPP} \\ \frac{dP}{dV} < 0, \text{ right of MPP} \end{cases} \quad (1)$$

The above equation can be stated in terms of voltage and current as [16–18].

$$\begin{aligned} \frac{dP}{dV} &= \frac{d(IV)}{dV} \\ &= I + V\frac{dI}{dV} \end{aligned} \quad (2)$$

When the operating point is at MPP then dP/dV = 0; Eq. (2) can be rearranged as

$$I + V\frac{dI}{dV} = 0$$

Therefore,
$I + V\frac{dI}{dV} = 0$

$$\frac{dI}{dV} = -\frac{I}{V} \tag{3}$$

From the above Eq. (3) [18], it can be concluded that left side of the equation shows photovoltaic module's incremental conductance (dI/dV) and right side of the equation shows photovoltaic module's instantaneous conductance (I/V). Therefore, during the tracking process, operating point continue to perturb until incremental conductance value (dI/dV) equals the instantaneous conductance value or (I/V). The other two conditions when the slope of photovoltaic module power curve is on the left of the MPP (dP/dV > 0) and when it is on the right of the MPP (dP/dV < 0) can be expressed in terms of voltage and current by rearranging Eq. (2) as

$$\frac{dI}{dV} > -\frac{I}{V} \tag{4}$$

$$\frac{dI}{dV} < -\frac{I}{V} \tag{5}$$

Here, dI and dV represent change in current and voltage before and after the increment respectively, whereas I and V represent instantaneous values of voltage and current, respectively. The above two Eqs. (4) and (5) helps in determining the direction of perturbation so that operating point moves towards the direction of maximum power point. All these equations can be summarized as [18].

$$\begin{cases} \frac{dI}{dV} = -\frac{I}{V}; \text{ when } \frac{dP}{dV} = 0; \text{ at MPP} \\ \frac{dI}{dV} > -\frac{I}{V}; \text{ when } \frac{dP}{dV} > 0; \text{ at left of MPP} \\ \frac{dI}{dV} < -\frac{I}{V}; \text{ when } \frac{dP}{dV} < 0; \text{ at right of MPP} \end{cases} \tag{6}$$

Figure 3 shows how the operating point in the Incremental Conductance Method perturbs to reach Maximum Power Point (MPP). The pattern and approach of perturbation in the incremental conductance method is the same as that of perturb and observe method. From Fig. 3, it can be observed that when the operating point is in the left side of MPP, the direction of perturbation is positive whereas the direction of perturbation has to be changed (or reversed) when the operating point is at the right of MPP.

Condition I: When (dI = 0 and dV = 0) that means there is no change in voltage and current; it concludes that operating point is on the maximum position and MPPT

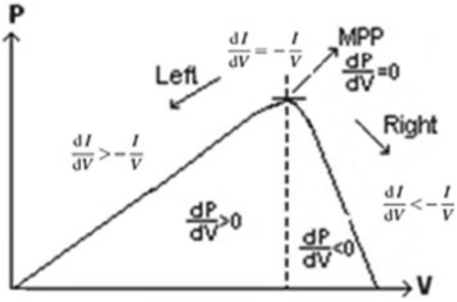

Fig. 3 Basic concept of incremental conductance method on P–V curve

still operates on maximum power point. Atmospheric conditions under this condition remains unchanged.

Condition II: When only change in current is accounted and there is no change in voltage; (dV = 0 and dI changes). Change in dI indicates a change in atmospheric conditions results in a change in solar irradiance, which leads to a change in maximum power point. When dI > 0 then there is a rise in the amount of solar irradiance which results in voltage of maximum power point.

Condition III: When current and voltage both changes and both do not equal to zero (dI/dV $\neq$ 0). In case, if both voltage and current are changing then Eqs. (4) and (5) helps in determining the direction of perturbation to reach maximum power point. If dI/dV > -I/V, then dP/dV > 0, this indicates that operating point on P–V curve is toward the left of the MPP.

Figure 4 explains the whole process, about how MPPT in combination with DC-DC converters is used to extract maximum power from the solar photovoltaic module or array.

Figure 4 shows that voltage V_{pv} and current I_{pv} obtained from solar panel are input to control algorithm. Control algorithm may be P&O method or Incremental Conductance method, implemented to track maximum power point condition by perturbing duty cycle. PWM (Pulse-Width Modulation) controller helps in adjusting and monitoring duty cycle (α) used for triggering purpose of power electronic switch

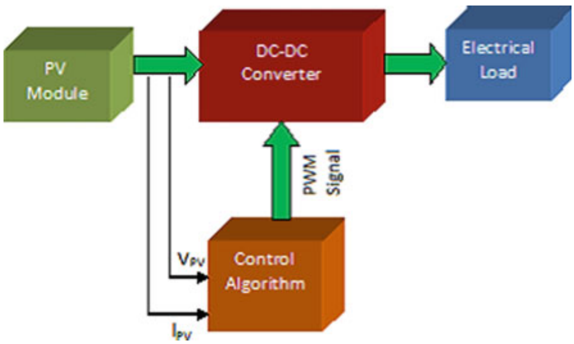

Fig. 4 Interconnection of solar photovoltaic module and load through DC-DC converter using control mechanism

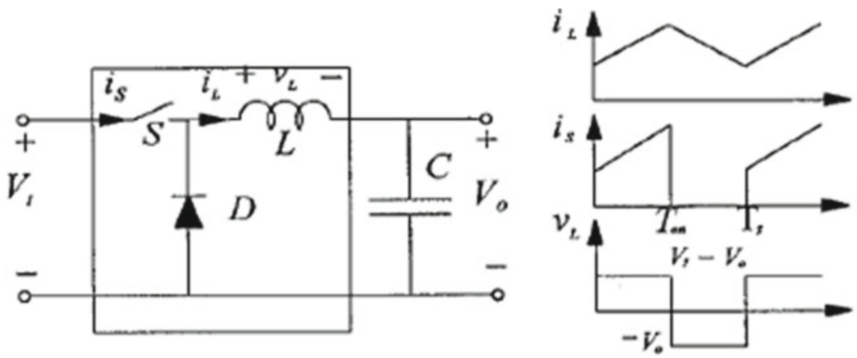

Fig. 5 Schematic diagram of Buck converter and waveforms

(i.e., MOSFET) of DC-DC Converter. Duty cycle (α) of the converter is controlled in such a way that the source will send maximum power to the load.

(c) **Types of DC-DC Converters**

1. Buck Converter,
2. Boost Converter, and
3. Buck–Boost Converter.

c1. **Buck Converter**

Buck Converter is generally used when photovoltaic module or array voltage (input voltage) is high and battery voltage (output voltage) is low. It is also termed as step-down converter (Fig. 5).

In Buck Converter, switch S operates at a higher frequency to produce a chopped output voltage. By adjusting on/off duty cycle of the switching, power flow is controlled. The average output voltage is given by [19]

$$\frac{V_o}{V_i} = \frac{t_{on}}{T} = D \tag{7}$$

c2. **Boost Converter**

Boost Converter is generally used when a photovoltaic module or array voltage (input voltage) is low and battery voltage (output voltage) is high. It is also known as a step-up converter (Fig. 6).

The average output voltage for boost converter is given as [20]

$$\frac{V_o}{V_i} = \frac{T}{T_{off}} = \frac{1}{1 - D} \tag{8}$$

c3. **Buck–Boost Converter**

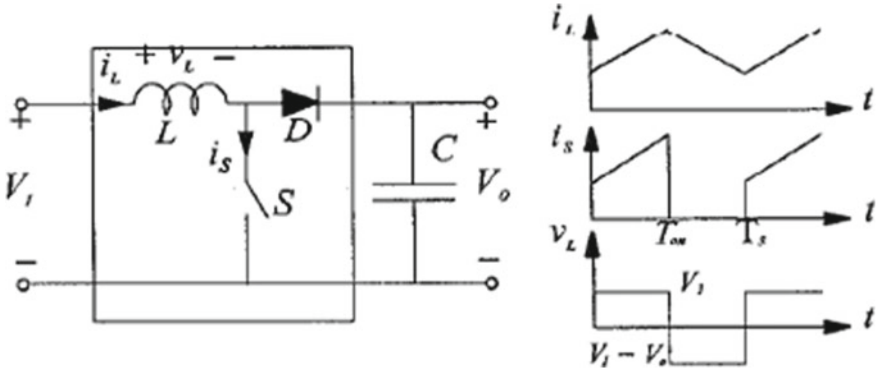

Fig. 6 Schematic diagram of boost converter and waveforms

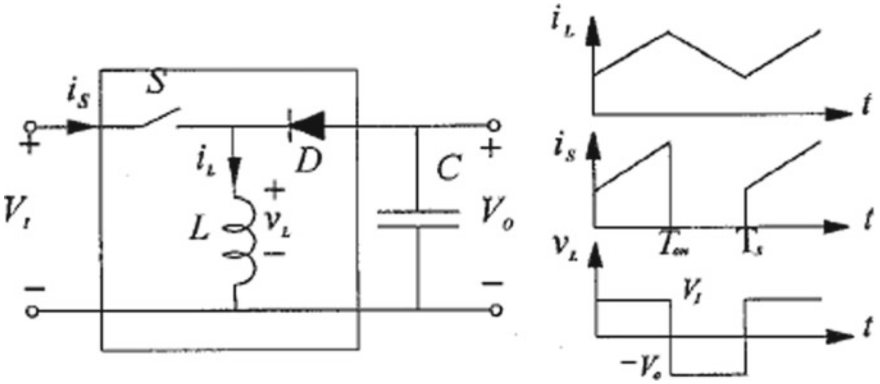

Fig. 7 Schematic diagram of Buck–Boost converter and waveforms

Buck–Boost Converter generally used when battery voltage (output voltage) is either high or low than the input voltage. It can be used as a step-up or step-down converter (Fig. 7).

The average output voltage for Buck–Boost converter is given by [21]

$$\frac{V_o}{V_i} = \frac{t_{on}}{t_{off}} = \frac{D}{1 - D} \tag{9}$$

4 Results and Discussion

The MATLAB/Simulink Models of Photovoltaic Module and Implementation of MPPT Methods are as follows:

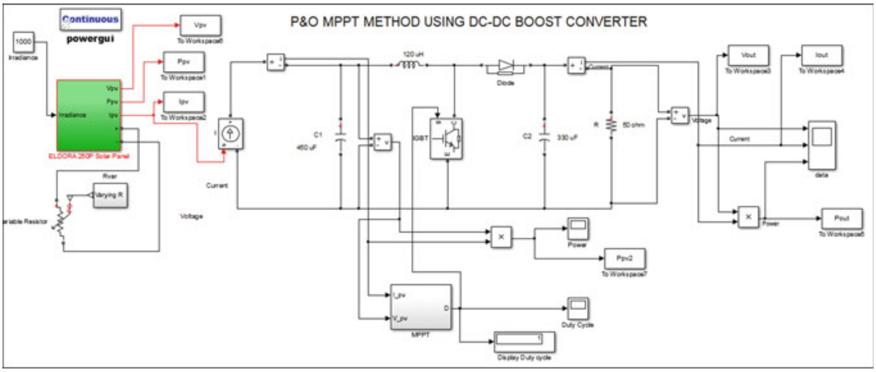

Fig. 8 MATLAB/Simulink Blocks of Perturb and Observe (P&O) MPPT Method

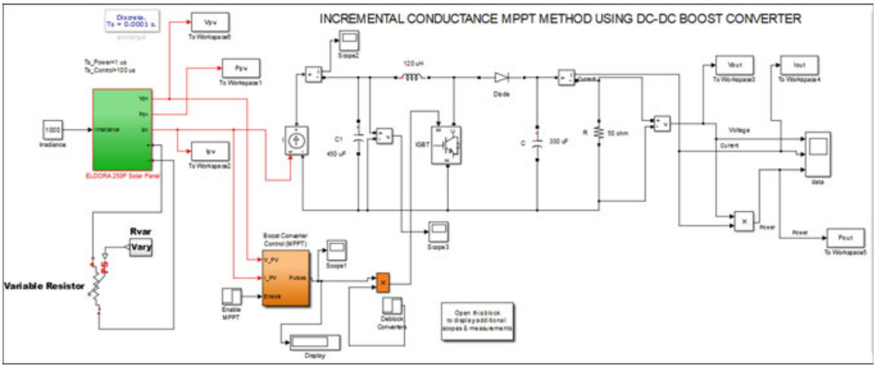

Fig. 9 MATLAB/Simulink Blocks of Incremental Conductance (INC) MPPT Method with DC-DC boost converter

ELDORA-250P, 60 cell polycrystalline solar photovoltaic module manufactured by Vikram Solar Pvt. Ltd., is proposed as a reference model for evaluating and validating the simulated photovoltaic model designed in MATLAB/Simulink. ELDORA-250P is a highly efficient solar photovoltaic module comprising 60 polycrystalline solar cells, ideally used in rooftop and ground-mounted applications.

Simulated results are compared with the practically and commercially available ELDORA-250P module for validating the proposed simulated module. An ideal ELDORA-250P solar photovoltaic module is developed in MATLAB/Simulink environment by considering series resistance $R_s = 0\ \Omega$ and shunt resistance $R_{sh} = \infty$. I-V Characteristics of the proposed model ELDORA-250P at different solar irradiance and at constant temperature of 25 °C are shown in Fig. 10, which are used as a reference for validating the characteristics to be obtained from the photovoltaic module designed in this thesis.

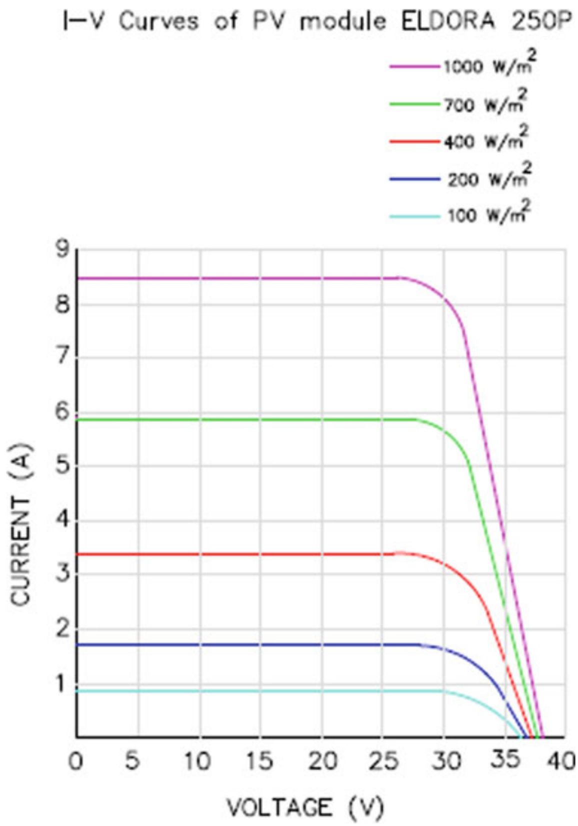

Fig. 10 V-I characteristic curves of ELDORA-250P at constant temperature 25 °C and varying solar irradiance

According to the specification of ELDORA-250P solar photovoltaic module, basic parameters, which are required to design a photovoltaic module at Standard Test Condition (STC), are given in Table 2 of the manufacturer's datasheet.

The output power of a solar photovoltaic module is affected mainly due to change in atmospheric conditions and the two major environmental factors, responsible for influencing output power of solar photovoltaic module, are power density of sunlight,

Table 2 Commercial photovoltaic module ELDORA-250P datasheet at STC with solar irradiance 1000 W/m^2 and temperature 25 °C

Module parameters	ELDORA-250P
Maximum power, P_m (W)	250
Maximum voltage, V_m (V)	30.58
Open circuit voltage, V_{oc} (V)	37.55
Short circuit current, I_{sc} (A)	8.71
NOCT	45 °C ± 85 °C

i.e., solar irradiance (W/m^2) and working temperature (°C). Simulated Model of ELDORA-250P is tested for two different conditions using MATLAB/Simulink, which are.

1. Constant temperature and varying solar irradiance,
2. Constant solar irradiance and varying module temperature.

Parameters obtained after simulation at constant solar irradiance (1000 W/m^2) and varying module temperature (25 °C, 35 °C, 45 °C, 55 °C, 65 °C, and 85 °C) are given in Table 3.

Simulated results of photovoltaic module parameters obtained from simulated I-V and P–V characteristic graphs are compared against corresponding actual results of commercially available ELDORA-250P module parameters which are given in Table 4.

Table 3 Module parameters extracted after simulation at different temperature level and at constant solar irradiance of 1000 W/m^2

Module parameters	Temperature (°C)					
	25 °C	35 °C	45 °C	55 °C	65 °C	85 °C
Maximum power, P_m (W)	257.6	246.6	238.3	228.1	216.8	198.1
Maximum voltage, V_m (V)	32.1	29.38	28.88	28.26	27.55	24.38
Open-circuit voltage, V_{oc} (V)	37.2	36.04	34.88	33.72	32.55	30.2
Short-circuit current, I_{sc} (A)	8.71	8.74	8.78	8.81	8.84	8.91

Table 4 ELDORA-250P commercial module validation with the simulated module at STC with solar irradiance of 1000 W/m^2 and at 25 °C temperature

Module parameters	ELDORA-250P (Actual Results)	ELDORA-250P (Simulated Results)	% Error = (Actual Results-Simulated Results)/Actual Results × 100%
Maximum power, P_m (W)	250	257.6	3.04%
Maximum voltage, V_m (V)	30.58	32.1	4.97%
Open-circuit voltage, V_{oc} (V)	37.55	37.2	0.93%
Short-circuit current, I_{sc} (A)	8.71	8.71	0.00%
NOCT	45 °C ± 85 °C		

Table 5 Comparison of simulated results of P&O and INC MPPT methods

MPPT method	Output Power P_{out} (Watt)	Output voltage V_{out} (Volts)	Output current I_{out} (Ampere)
(P&O) method	797.47	199.68	3.99
INC method	897.75	211.86	4.23

From Table 4, it can be easily understood that simulated results obtained at STC are approximately nearer to the actual results with small deviations, which may be considered as negligible and are articulated in the form of % error.

DC-DC boost converter is modeled in MATLAB/Simulink for enhancing power to be received from ELDORA-250P simulated photovoltaic module using Perturb & Observe (P&O) and Incremental Conductance (INC) MPPT controller; both MPPT controllers are also designed in MATLAB/Simulink controlling the switching action of MOSFET. Both the MPPT controllers control duty cycle used for triggering MOSFET of the DC-DC boost converter. Load resistance of 50 Ω is connected across Simulink model of the DC-DC boost converter.

DC-DC boost converter designed in MATLAB/Simulink consists of two capacitors, one with a rating of 450 μF and another with a rating of 330 μF, one inductor of 120 μH, one resistive load of 50 Ω, one power diode, and one MOSFET. Both the MPPT methods are tested using simulated ELDORA-250P photovoltaic module at standard test condition (STC) having solar irradiance of 1000 W/m^2 and temperature of 25 °C.

Results obtained after simulation are as follows:

Simulated results achieved from both the MPPT methods after simulation are analyzed in tabulated form in Table 5.

5 Conclusion

The proposed photovoltaic module built in MATLAB/Simulink illustrates and verifies nonlinear I-V and P–V characteristic curves of the photovoltaic module. Essential parameters are obtained from simulated I-V and P–V graphs which are mentioned in Table 2. After analyzing the simulated I-V and P–V characteristics, it is concluded that with the increase in solar irradiance, both open-circuit voltage V_{oc} and short-circuit current I_{sc} of photovoltaic module increases, thereby increasing the output power of the photovoltaic module. The reason behind the increase in output power is the logarithmic dependence of open-circuit voltage V_{oc} on solar irradiance whereas short-circuit current I_{sc} is directly proportional to the solar irradiance.

When photovoltaic module is built in MATLAB/Simulink under different temperature levels and at constant solar irradiance and simulated I-V and P–V characteristic graphs are generated. Essential parameters are obtained from simulated I-V and P–V graphs which are mentioned in Table 3. After analyzing the simulated

I-V and P–V characteristics, it is concluded that with the increase in module's working temperature, short-circuit current I_{sc} of photovoltaic module increases marginally whereas open-circuit voltage V_{oc} of photovoltaic module decreases drastically, thereby decreasing the output power of the photovoltaic module. Hence, it is concluded that temperature has a significant effect in determining solar photovoltaic module's efficiency and performance of the photovoltaic module is highly affected by the increase in the module's working temperature.

Advantage of using DC-DC boost converter amongst the other converters is that in case if MPPT circuit fails to operate and switching action of MOSFET will not take place, therefore in this condition load is directly connected to the panel and panel will still supply power to the load but at less efficiency. Other DC-DC converters cannot fulfil this condition. This paper describes only about implementation of boost converters.

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