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Development of Mathematical Model of Photovoltaic Module and The Effect of Change in Parameters on its Performance

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Abstract : Photovoltaic (PV) is one of the leading renewable energy resources, and its performance is prone to changes in parameters and connections, which may lead to faults in the system. In this paper, a mathematical model of a PV module is developed in the MATLAB-Simulink platform and the effect on I-V and P-V characteristics, due to changes in parameters is discussed. Further, a PV array system is developed with mathematical model of PV module and is connected with MPPT, boost converter and DC load to create a standalone system**.**

***Keywords* - PV module mathematical model, temperature, irradiance, PV parameters**

1. Introduction

Solar photovoltaic (PV) power generation is the most advantageous source among others like wind and ocean power as it is abundant worldwide. PV technology has been widely used to generate electricity across the globe in recent years. It gains popularity because it can generate electricity as a stand-alone system and able to export excess power to conventional grid systems with a grid integration feature. The consumer thereby receives a steady supply of electricity and experiences less dependence on conventional electrical sources.

Photovoltaic is the conversion of light directly into electricity through semiconductor materials (PV cells). The output of a single solar cell is around 0.6-0.7 V DC, which is too small to supply the energy for practical use. Hence, number of PV cells are interconnected to form PV module and these modules are connected in series-parallel combination to form PV array and get workable voltage and current. It may be analysed with I-V and P-V characteristics of PV module. As the PV generation depends upon on the intensity of sunlight, the electrical parameters of PV module will change with irradiance and temperature [1]. Therefore, it is important to extract the maximum power from module under different conditions. Maximum power point tracker (MPPT) is used to track and extract the maximum power from PV module by changing the maximum power point location under varying conditions [2]. This paper covers the development of PV array mathematical model using the MATLAB-Simulink platform. Then the effects on electrical characteristics during changes in parameters like irradiance and temperature are discussed.

2. PV System Modeling

The PV system structure is made up of several parts, including a PV array, a maximum power point tracker (MPPT), a converter, cables, junction boxes, distribution panels, support structures, etc. Figure 1 illustrates these numerous parts [3].

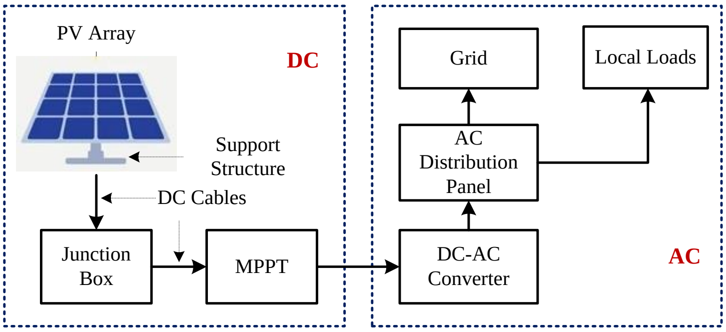

Figure 1. Structure of PV system

A PV array is a PV module's series and parallel configuration, which produces sufficient voltage and current, respectively. The PV modules are connected with each other through junction boxes and cables. The output of PV array is given to MPPT. The objective of MPPT is to ensure that the PV array will operate at the maximum power point (MPP). MPPT trying to track the maximum power by varying the duty cycle of the DC converter. Further, the converter converts the DC power into AC and distributed it to local loads through the AC distribution panel. Provision is also made for the transfer of additional AC power to the grid.

2.1 Single diode model of PV cell

The equivalent circuit of the PV cell's mathematical model, which is based on the single-diode model, is depicted in Figure 2. Here, the output of PV cell is represented by a current source (I_{Ph}) connected in parallel with a single diode (D). The current I_d flows through diode whereas I_{sh} flows through shunt resistance (R_{sh}). Finally, the current (I) flows through series resistance (Rs) and collected at the output of PV cell. The PV cell's equations based on single diode model are mentioned below [4].

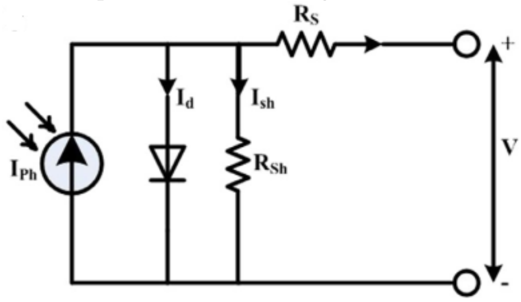

Figure 2. Equivalent circuit of PV cell

I= $I_{ph} - I_d - (V_d/R_{sh})$ …… (1)

$V_d = V + IR_s$ …… (2)

$I_d = I_s\left\{e^{\frac{qV_d}{nKT_{ak}}} - 1\right\}$ ……. (3)

$I = I_{ph} - I_s\left\{e^{\frac{qV_d}{nKT_{ak}}} - 1\right\} - (V + IR_s)/R_{sh}$ ……. (4)

$I_s = I_{rs}\,(\frac{T_{ak}}{T_{rk}})^3 * [e^{\{(qE_{go})(\frac{1}{T_{rk}}-\frac{1}{T_{ak}})\}/(nK)}]$ …… (5)

$I_{rs} = \frac{Isc}{e^{\frac{(q*V_{oc})}{Ns*K*n*T_{ak}}} - 1}$ ……. (6)

$I_{ph} = I_{sc} + K_i\,(T_{ak} - T_{rk}) * \frac{G}{1000}$ ……. (7)

I - Output current

V - Voltage across the PV module

V_{OC} - Open circuit voltage

V_d – Voltage across diode

I_s - Saturation current

I_{rs} - Reverse saturation current

I_{Ph} - Photocurrent

T_{ak} - Operating temperature of a cell (T)

T_{rk} - Nominal temperature (298K)

K - Boltzmann constant (1.38 x 10^{-23} J/K)

n - Ideality factor (varies from 1 to 2)

K_i - Temperature coefficient of I_{sc}

G - Insolation on the solar cell

I_{sh}–Shunt current

2.2 Mathematical modeling of PV array

Based on mathematical equations, a model of PV module is developed in the MATLAB-Simulink platform and is shown in Figure 3(a) & 3(b). Further, five PV modules are connected in series to form a string and five such parallel strings are connected to form a PV array, shown in Figure 3 (c). Power can be determined by connecting the current and voltage measurement units in series and parallel to measure the data. The PV array's output voltage (V_PV) and current (I_PV) is fed to MPPT controller. MPPT controller works on Perturb and Observe (P&O) technique to track the maximum power point at every instant by controlling the duty cycle (D). Further, the duty cycle is fed to DC-DC PWM generator to generates a modulated signal (PWM). PWM signal is given to the boost converter, connected with the PV array. The PV array connected with boost converter and DC load forms a standalone system as shown in Figure 4. The reason to connect boost converter with PV array is to get controlled voltage. The output of boost converter may be used to converter DC output into AC output, which can be connected with the grid [5-6].

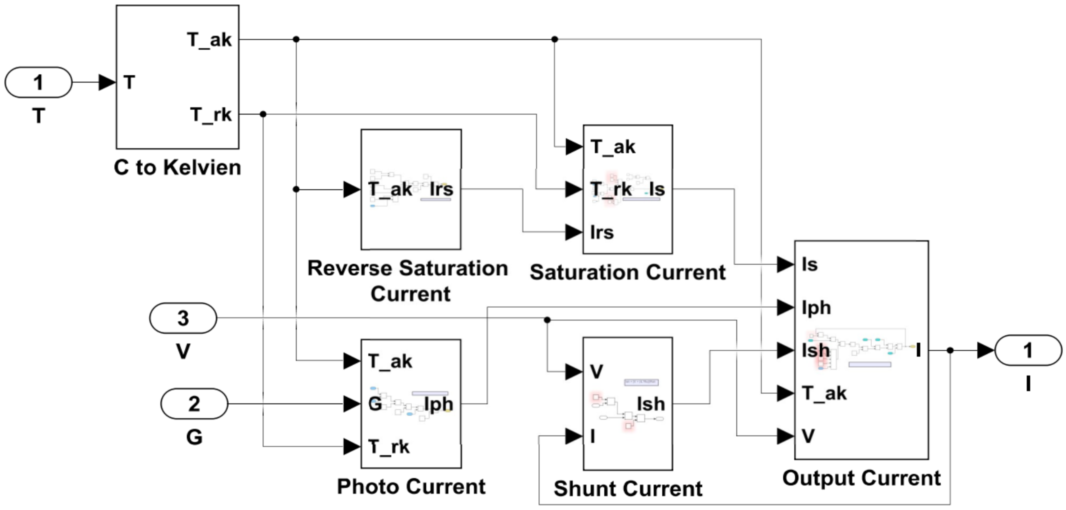

Figure 3(a) Mathematical model of PV module

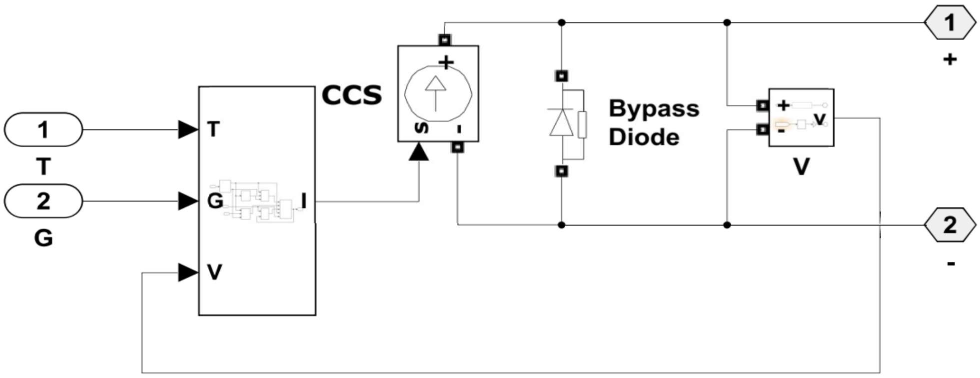

Figure 3 (b) PV module connection

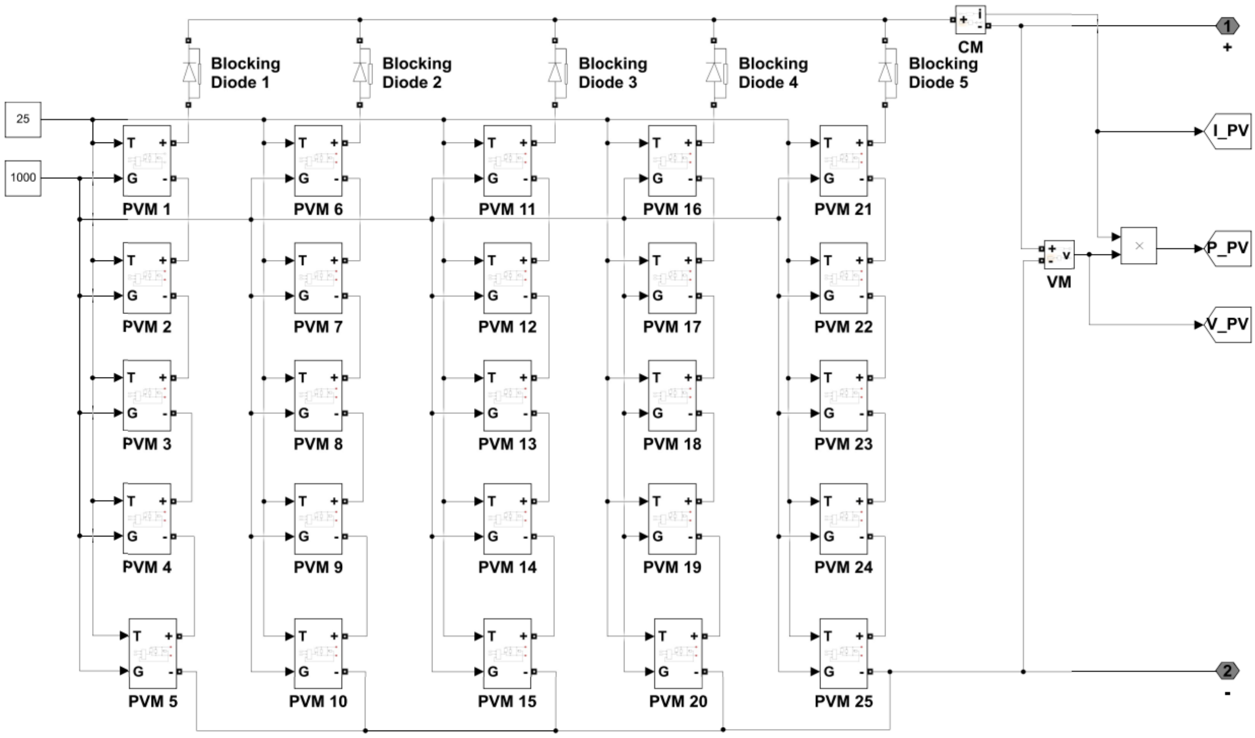

Figure 3 (c) PV modules connected in series and parallel

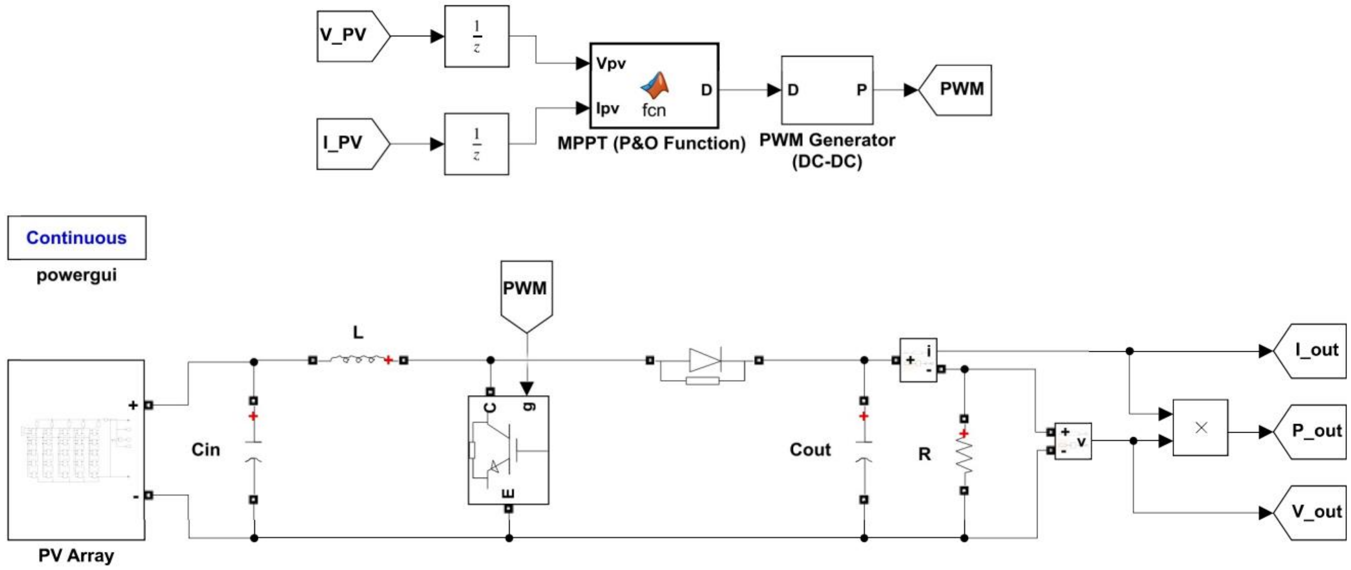

Figure 4. PV Array model connected with MPPT and Boost Converter

A commercial multi-crystal PV module, KC200GT-200W has been used as the reference module for further discussion. Table 1 provides the details from the datasheet of the KC200GT module as provided by the manufacturer [7]. As each module is capable to generate 200W power at standard testing condition (STC), developed PV array model (5x5 PV modules) may generate 5 kW power at STC.

Table 1. PV module specification at STC (1000 w/m^2 and 25°C)

Parameters	Values
Maximum power	200 W
Maximum Power Voltage (Vmpp)	26.3 V
Maximum Power Current (Impp)	7.61 A
Short circuit current (Isc)	8.21 A
Open circuit voltage (Voc)	32.9 V
Ideality factor (n)	1.3
Temperature coefficient of ISC (Ki)	0.0032 A/0C
Number of series-connected PV cells (Ns)	54

I-V and P-V characteristics of developed PV array model are shown in Figure 4(a) and 4(b) respectively. During short circuit condition, the terminal voltage of the array decreases to zero and the short-circuit current (ISC) attains maximum value. Whereas, in the case of an open-circuited situation, the current reaches to zero and the voltage at this condition is called open-circuit voltage (VOC). The maximum power is represented as Pmax in the P-V curve. The voltage and current corresponding to Pmax are represented as Vmp and Imp, respectively. Generally, the PV system is preferred to work at the point of maximum power using the maximum power point tracking algorithm (MPPT).

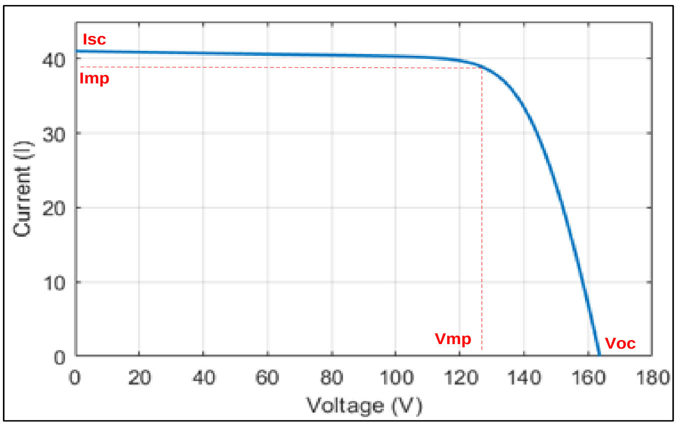

Figure 4(a). I-V Characteristic of PV Array

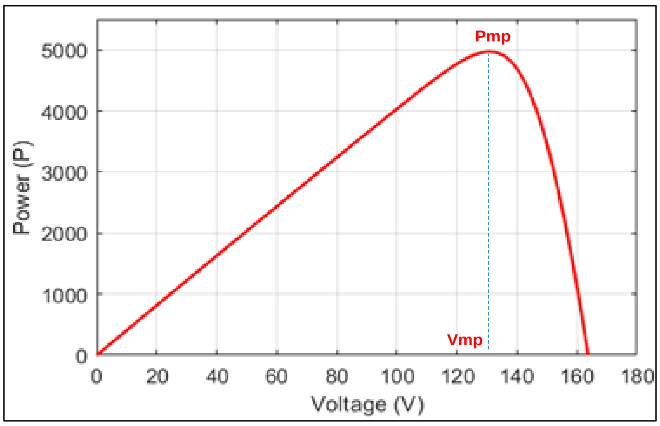

Figure 4(b). P-V Characteristic of PV Array

3. Effect on I-V and P-V characteristics of PV array with the change in parameters

The constructed model has advantages for studying how environmental factors like temperature change, irradiation, and shading influence [8-9]. Figures 5(a) and (b) display the I-V and P-V characteristics at various temperatures and constant irradiation. Here, the temperature fluctuates between 15 to 45°C in steps of 10°C. As a result, while the output voltage decreases dramatically as the working temperature rises, only a very minor increase in the output current is observed. As a result, as the temperature rises, the PV array's overall output power decreases.

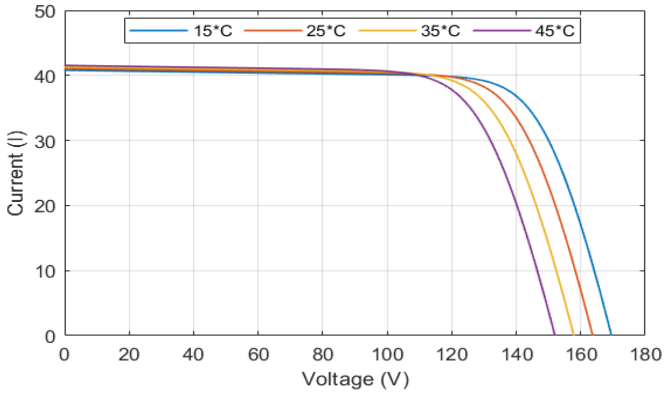

Figure 5(a). I-V characteristic of PV Array with change in temperature

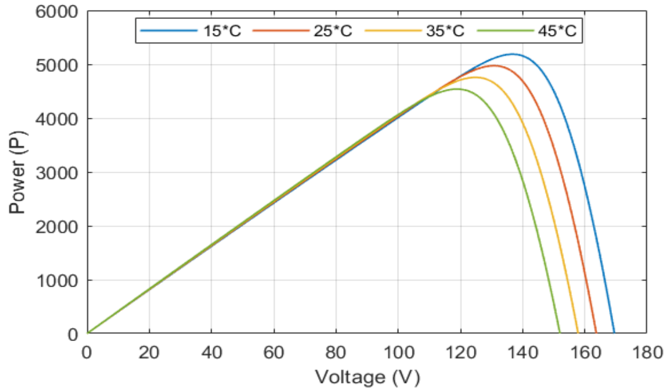

Figure 5(b). P-V characteristic of PV Array with change in temperature

The I-V and P-V characteristics for various irradiation intensities at a constant temperature (25°C) are shown in Figures 6(a) and (b). Here, the sun irradiation decreases from 1000 W/m2 to 700, 500, and 300 W/m2. As a result of the decreased irradiation, the current and voltage of the PV array rapidly decrease. As a result, the PV array produces less electricity overall as a result of the decrease in irradiation.

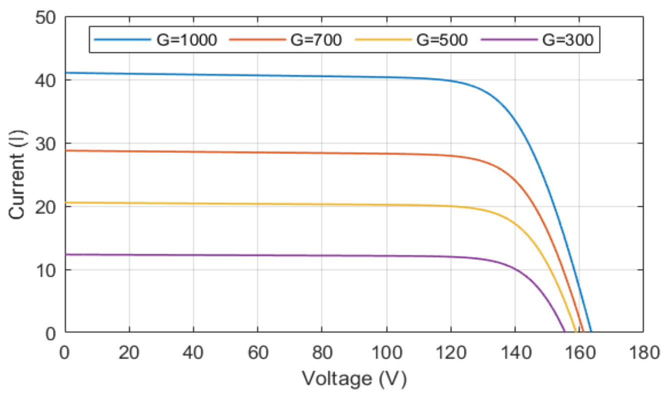

Figure 6(a). I-V characteristic of PV Array with change in irradiation

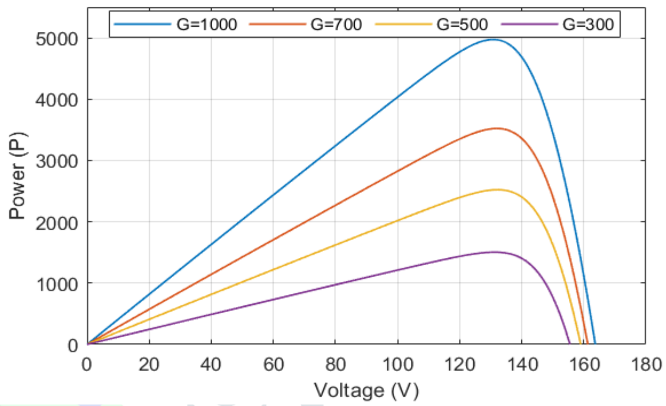

Figure 6(b). P-V characteristic of PV Array with change in irradiation

The power generation of the proposed PV array varies with irradiance. Sometimes, the uneven distribution of irradiance over the PV array, called shading, may cause some modules to receive less radiation than others. The shading may occur due to a tree, building, cloud, etc. When shading covers, power generation from PV array decreases rapidly [10]. As shown in Table 2, various shading patterns are considered in this study to assess how shade affects the performance of solar PV arrays. Figures 7(a) and 7(b) display the I-V and P-V properties in shady circumstances. The partial shading condition brings about the local maximum of MPP by reducing the current generation and so introducing the reduced multiple peaks.

Table 2. Different cases of shading over PV array

Case	Description
1	No shaded module, all modules receive irradiation of 1000 w/m^2
2	One shaded module (PVM-5) receives irradiation of 500 w/m^2 and remaining modules receives 1000 w/m^2
3	Two shaded modules (PVM-5 receives irradiation of 500 w/m^2 and PVM-1 receive 200 w/m^2) and remaining modules receives 1000 w/m^2
4	Three shaded modules (PVM-5 receives irradiation of 500 w/m^2, PVM-1 receive 200 w/m^2 and PVM-10 receives irradiation of 700 w/m^2) and remaining modules receives 1000 w/m^2

It is challenging to protect PV arrays against shadowing. However, a big, open space is preferred so that the PV array will not be cast in shadow by a nearby structure or tree. However, a bypass diode, shown in Figure 3(c), can reduce the impact of shadowing; thereby power generation can be enhanced [11].

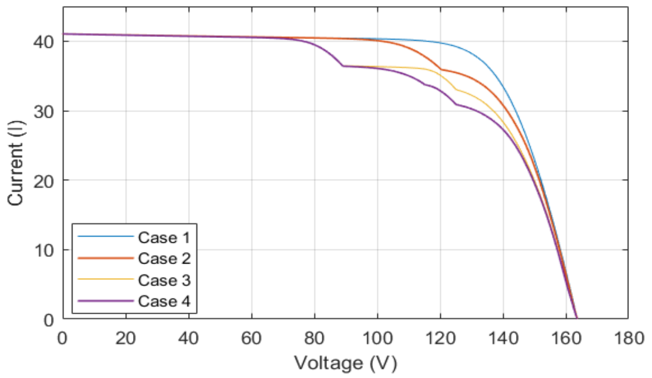

Figure 7(a). I-V characteristic of PV Array with shading effect

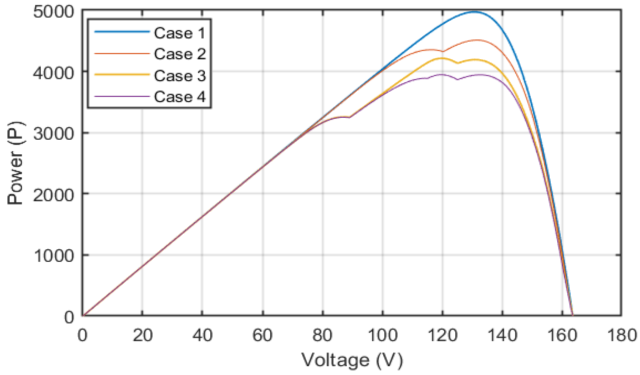

Figure 7(b). P-V characteristic of PV Array with shading effect

4. PV ARRAY AND BOOST CONVERTER OUTPUT

The output response of PV array is shown in Figure 8(a). The parameters set to get the optimum result for boost converter are mentioned in Table 3 [12]. The output response of Boost Converter is shown in Figure 8(b). Here the 5kW standalone PV array model is developed using mathematical model of PV array. The PV array is connected with boost converter and a resistive load, supplying constant output voltage of 220V DC at the boost terminals, which may be utilised to supply suitable DC loads.

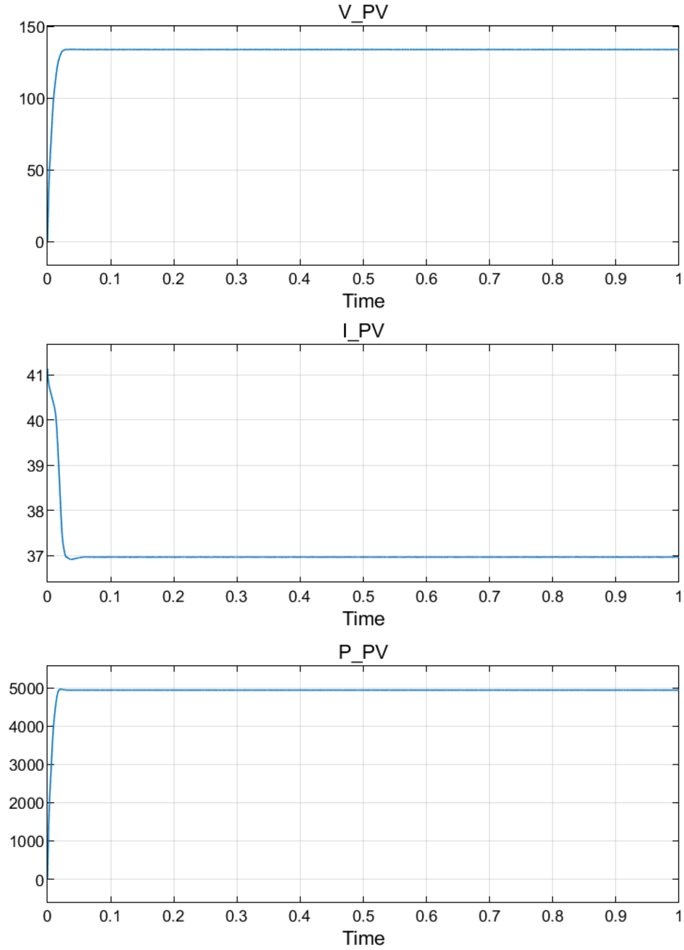

Figure 8(a). PV Array Output

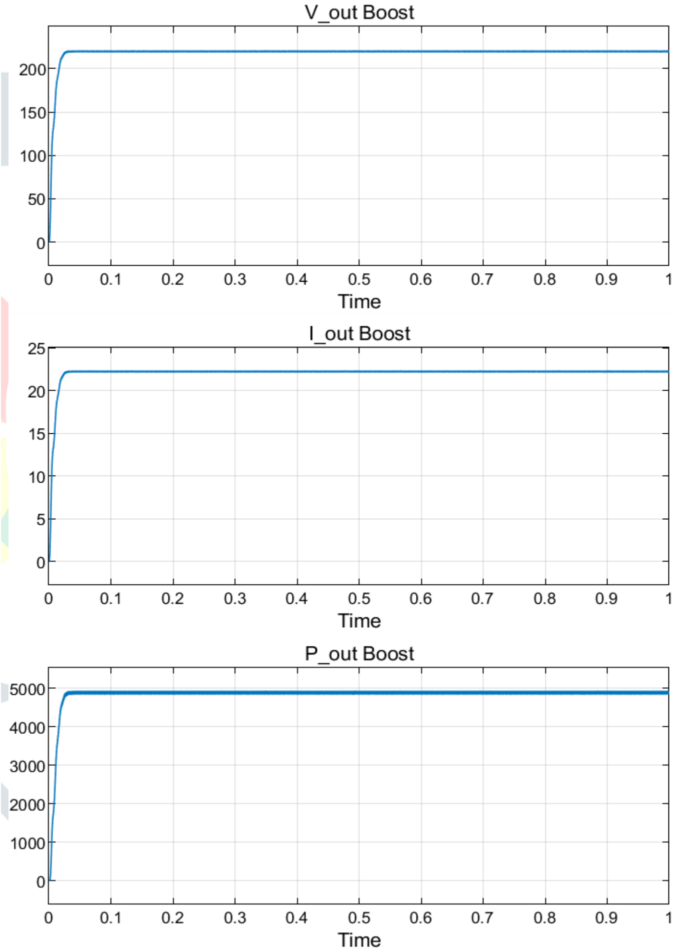

Figure 8(b). Boost Converter Output

Table 3. Boost Converter Parameters

Parameters	Values
Input Capacitor (Cin)	2000 µF
Inductor (L)	2 mH
Output Capacitor (Cout)	200 µF
Switching Frequency	20,000 Hz

5. CONCLUSION

The proposed mathematical modeling of PV module based on single diode model is implemented on the basis of their equivalent circuits using MATLAB-Simulink platform. The effect of change in parameters such as varying temperature and irradiation are investigated to study the behaviour of electrical characteristic. It is found that with the increment in temperature, voltage slightly decreases whereas current remains almost constant hence, power also decreases. Also, it is observed that when irradiance decreases there is significant drop in current compared to voltage and hence in PV array power generation. The effect of shading is also discussed in this paper. At the end the 5kW standalone PV array model is developed to supply DC loads

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