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Modeling, Simulation and Analysis of Photovoltaic Modules under Partially Shaded Conditions

S. Sheik Mohammed[1]*, D. Devaraj[2] and T. P. Imthias Ahamed[3]

[1]Kalasalingam University, Srivilliputhur - 626126, Tamil Nadu, India; ssheikmd@yahoo.co.in
[2]Department of EEE, Kalasalingam University, Srivilliputhur - 626126, Tamil Nadu, India; deva230@yahoo.com
[3]Department of EEE, T. K. M. College of Engineering, Kollam - 691005, Kerala, India; imthiasa@gmail.com

Abstract

The power output of photovoltaic (PV) cells is influenced by the environmental conditions, particularly by solar irradiation level. The irradiation level of light falling on all the cells in the module or the PV modules in an array is uneven under the cloudy weather conditions; this produces multiple peaks in the output of PV modules. It is essential to have a model of PV module in which the partial shading effect can be analyzed so that an effective Maximum Power Point Tracking (MPPT) system can be implemented for a PV system. This paper presents the modeling and performance analysis of PV modules under partial shaded conditions. A generalized PV module model is developed in MATLAB based on the mathematical equation of PV cell. The model is simulated for analysis of partially shaded cells in the PV module and also for partial shaded modules in the PV string for various weather conditions. The obtained results are satisfactory and confirm the accuracy of the developed PV module model. The developed model can be used for simulation and analysis of any PV modules under partially shaded conditions and also for development of PV power system with MPPT.

Keywords: MATLAB , Modeling, Partial shading, Photovoltaic, Simulation

1. Introduction

Photovoltaic (PV) based power systems had significant developments during the last few decades. There is a noticeable progress in implementation PV based power stations around the world due to its advantages such as low maintenance, easy installation, zero pollution. The first solar PV power station "*Arco Solar*" is implemented in California in the year of 1982 with a capacity of 1 MWp[1] and *"Solar star"* in California is the world's largest PV station by the end of 2015. The installed capacity of world's largest PV station is 579 MW[2]. The total worldwide PV capacity has reached to 178 GW by the end of 2014[3]. 55GW of worldwide deployment was forecasted for the year 2015 and the cumulative installed PV capacity is expected to be 540GW in 2020[4]. Figure 1 shows the projected growth of globally installed PV Capacity.

Modeling of PV modules using MATLAB is presented in many literatures[5–8]. A basic form of PV cell is comprised of a current source and a diode connected in anti-parallel to it[9]. The circuit model consists of resistor connected in series to the basic PV cell model is presented in[10]. Most of the presented works describes the modeling of PV under uniform irradiation and uniform temperature levels only. The shading effect on the PV modules greatly affects the power produced by the PV system. Partial shading of PV reduces the power produced by the PV modules and produces multiple peaks in the output power which affects the tracking performance of MPPT and makes the PV system less efficient. Analysis of PV characteristics under partial shading conditions through simulation would helps to develop a PV power system with effective Maximum Power Point Tracking controller. PV module modeling to study the partial shading effect is presented in many literatures. The work presented in[11] analyses the V-I characteristics of a PV module under partial shading. But, in practical cases the PV systems have multiple modules connected in series-parallel combination. Modeling

**Author for correspondence*

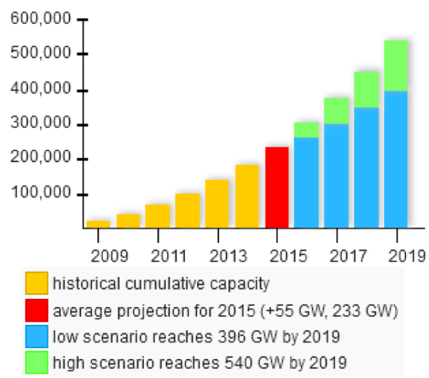


Figure 1. Projected growth of globally installed PV Capacity in MW[4].

of bypass diode configuration of PV module using Pspice is presented in[12]. Modeling and simulation of two diode model PV is presented in[13,14]. A two diode model with Bishop's model is presented in[13]. In[15], Solar cell modeling using Simscape tool is presented. This paper presents the modeling of generalized PV module developed using MATLAB/Simulink which can be used to analyze the V-I and P-V characteristics of PV Module, PV string and PV array under uniform irradiation and partial shading conditions. The model presented in this paper can be used to analyze the characteristics of any commercial PV module.

This paper presents the modeling and simulation of PV module in detail. Section 2, discusses the fundamentals of PV cell, PV module, PV string and PV array. In Section 3, the PV module development using MATLAB based on the mathematical equation is explained in steps. Simulation of PV module and PV series string under uniform irradiation and partial shading conditions are carried out, the results are presented and discussed in Section 4. The presented work is concluded in Section 5.

2. Photovoltaic Cell, Module, String and Array

Photovoltaic cells are a typical *pn* junction devices made out of semiconductor materials. Silicon is mostly used semiconductor material in PV manufacturing. PV cell converts the light directly into electricity. PV cells produce DC electricity when exposed to sunlight. The voltage output of PV cell is very low (say 0.7V *approx.*). Hence, the PV module is developed by connecting number of PV cell in series. The PV modules are connected in series or series-parallel combinations based on the requirements. PV string consists of a set of PV modules connected in series. A series parallel combination of PV modules is called as PV array. Figure 2(a) shows a PV cell. A PV module, PV string and PV array are shown in Figure 2(b), 2(c) and 2(d) respectively.

3. Modeling of PV Module using MATLAB

The equivalent circuit of simplified PV cell consists of a current source, a diode and a series resistor across the load as shown in Figure 3. The PV module is modeled in MATLAB/Simulink based on the mathematical equations. A step by step model development is discussed in this section.

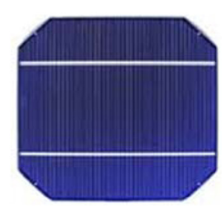
The output current of PV cell is expressed as

$$I = I_{pv} - I_d \quad (1)$$

The photocurrent (I_{pv}) and the diode current (I_d) in Equation (1) are expressed as follows

$$I_{pv} = [I_{sc} + K_I(T_c - T_r)] \cdot G \quad (2)$$

$$I_d = I_s\left\{\exp\left(\frac{q}{AkT_c}\right) - 1\right\} \quad (3)$$



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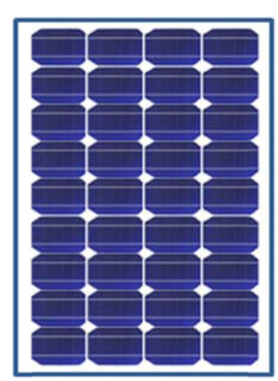

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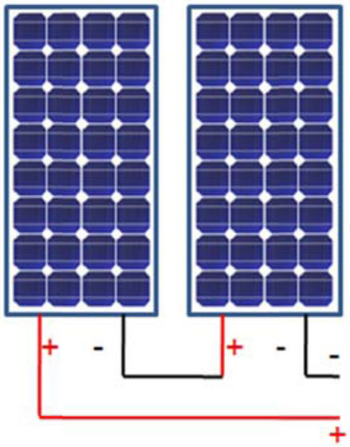

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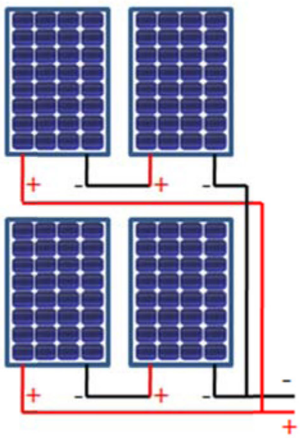


(d)

Figure 2. **(a)** PV cell. **(b)** PV module. **(c)** PV string. **(d)** PV array.

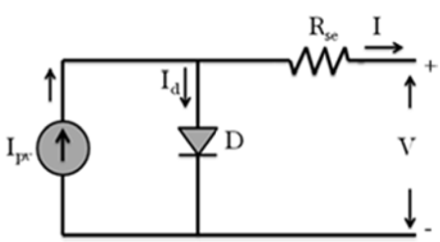


Figure 3. Equivalent circuit of Photovoltaic cell.

The simulation model represents Equation (2) and Equation (3) are shown in Figure 4 and Figure 5 respectively.

The saturation current of diode I_s in Equation (3) is calculated by using Equation (4) and the model for the saturation current calculation is shown Figure 6.

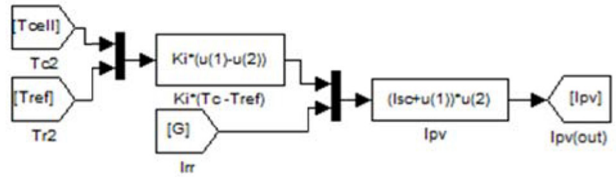


Figure 4. Calculation of I_{pv}.

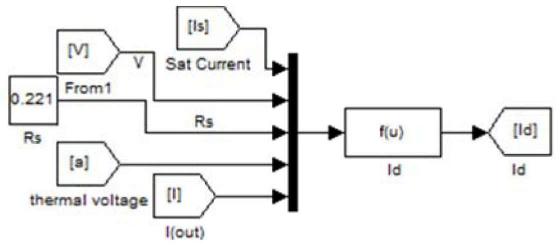


Figure 5. Calculation of I_d.

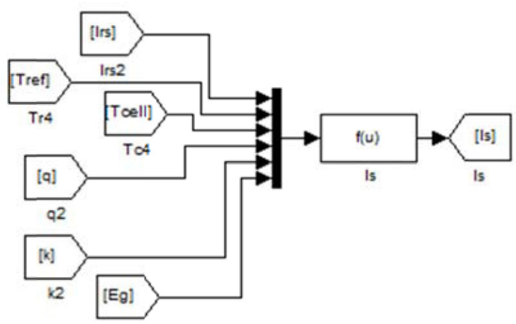


Figure 6. Calculation of diode saturation current I_s.

$$I_s = I_{rs}\left(\frac{T_c}{T_r}\right)^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_c}-\frac{1}{T_r}\right)\right] \quad (4)$$

The reverse saturation current I_{rs} is determined using Equation (5). Figure 7 is the simulation model to calculate the reverse saturation current

$$I_{rs} = \frac{I_s}{\exp\left(\frac{q}{AkT_{c(n)}N_s}V_o\right)-1} \quad (5)$$

The model has an input "a" which represents $a = \frac{q}{AkT_cN_s}$. The simulation model to calculate a is presented in Figure 8

The constant values associated with the equations are Eg, q,k. These values are assigned in the model as shown in Figure 9.

The proposed model is a generalized module model which can be used for the analysis of any commercial PV module. Hence, the model is created as subsystem and a subsystem dialog box is created for it to enter the values of the other important parameters which vary between modules. The PV module subsystem with a variable load is shown in Figure 10.

The subsystem dialog box of the developed model is shown in Figure 11. The dialog box will pop-up when user double click on the PV Module.

The ideality factor (*A*) of the PV cells vary depending upon the PV technology. Some of the most commonly used PV technologies are Monocrystalline Silicon (*A=1.2*) and Polycrystalline Silicon (*A=1.3*). So, a pop-up window is created in the dialog box to select *A*.

The temperature value should be in °Kelvin and the Irradiation value should be in kW/m^{2}for analysis. These values are generally given to the model in °C and W/m^2 as input to the module. Therefore, they are converted internally as shown in Figure 12.

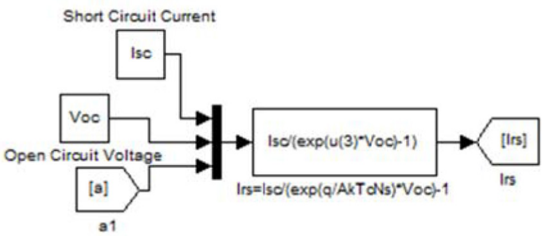


Figure 7. Calculation of I_{rs}.

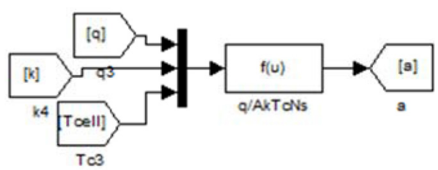


Figure 8. Calculation of *a*.

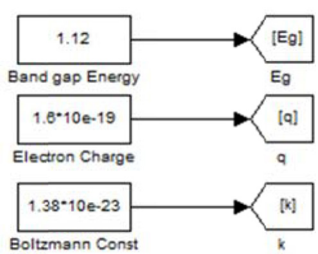


Figure 9. Insertion of constant values.

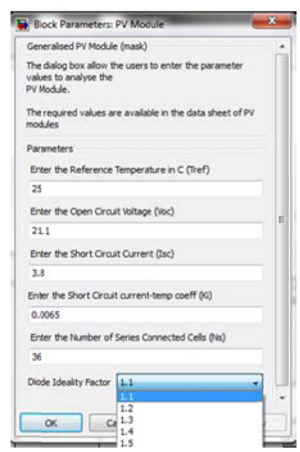


Figure 11. Subsystem dialog box.

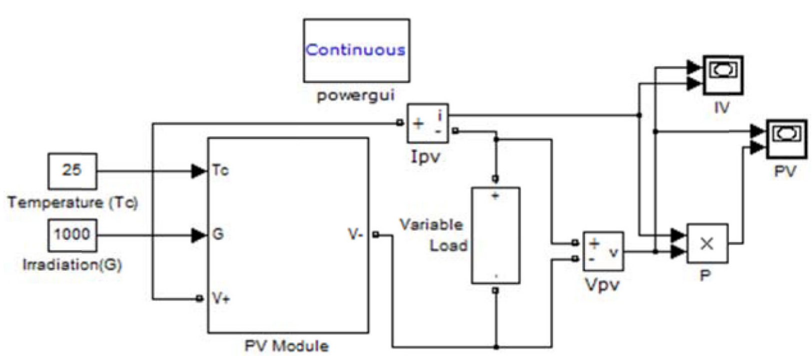


Figure 10. PV module subsystem with variable load.

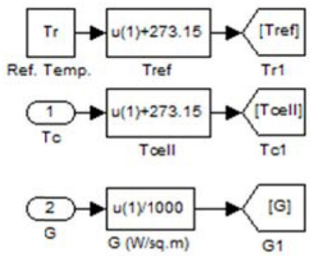


Figure 12. Unit conversion of T and G.

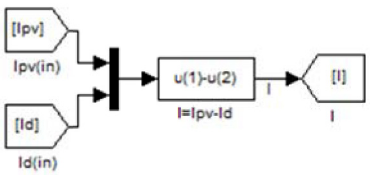


Figure 13. Output current calculation.

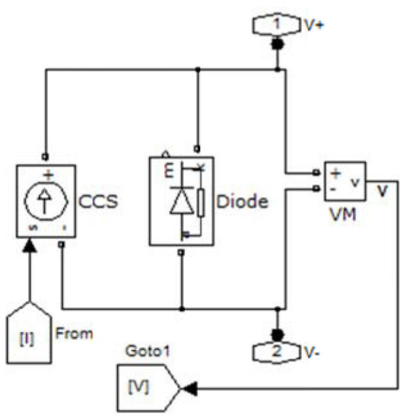


Figure 14. Bypass diode across the output of PV cell.

The output current of PV expressed in Equation (1) is calculated by the model shown in Figure 13.

The current produced by the cell will be low or there will be no current when a cell in the module is shaded. This causes hotspot heating in a module and leads to damage of module. The hotspot effect can be evaded with the help of bypass diode. Figure 13 represents the connection of bypass diode across the output of PV cell. The variable load is connected across *"V+"* and *"V-"* shown in Figure 14.

4. Simulation and Analysis

The PV module model is simulated for various weather conditions and the resulted are produced. Solarex MSX 60 PV[16] Module is selected for this study. The module parameters are given in Table 1.

4.1 Voltage-Power Characteristics of MSX 60 PV Module

The output characteristics of MSX 60 PV module is validated for uniform irradiation. The Voltage-Power characteristics of MSX 60 PV under various irradiation level at T = 25 °C and various temperature level at G = 1000W/m^2 are shown in Figure 15(a) and 15(b) respectively.

4.2 Partial Shading of PV Module

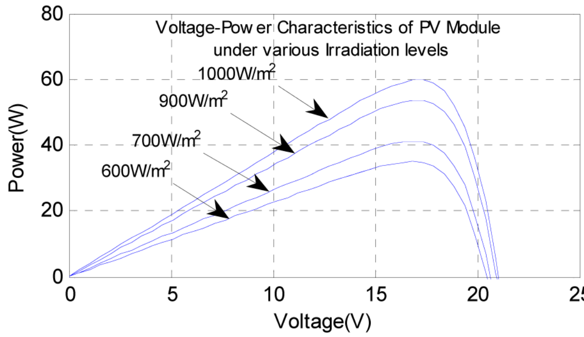
MSX 60 PV module has 36 cells in it. To analyze shading effect on a single PV module, the module is divided into 3 regions (12 cells) and different irradiation values are applied to each region.

The irradiation value is applied as G1 = 650 W/m^2, G2 = 850 W/m^2, and G3 = 950 W/m^2. Figure 16(a) shows the V-P characteristics of PV module under partial shading of cells. The output characteristics of PV module under uniform irradiation for standard test conditions (T=250C and G=1000 W/m2) are also shown in Figure 16(a). It can be noticed that the output power of PV coincides with the data sheet information. Figure 16 (b) shows the V-I characteristics of PV module for the above said partial shading conditions and uniform irradiation.

The partial shading analysis is carried out for 50% shading of PV modules. In this case 18 out 36 cells are set with G1=1000 W/m^2 and the irradiation of remaining 18

Table 1. Specification of solarex MSX60 PV

Description	**MSX 60**
Maximum Power (P_{max})	60W
Voltage @ P_{max} (V_{max})	17.1A
Current at @ P_{max} (I_{max})	3.5A
Guaranteed Minimum P_m	58W
Short Circuit current (I_{sc})	3.8A
Open Circuit voltage (V_{oc})	21.1A
Temperature co-eff of V_{oc}	-(80±10) mV/°C
Temperature co-eff of I_{sc}	(0.065±0.15) %/°C



(a)

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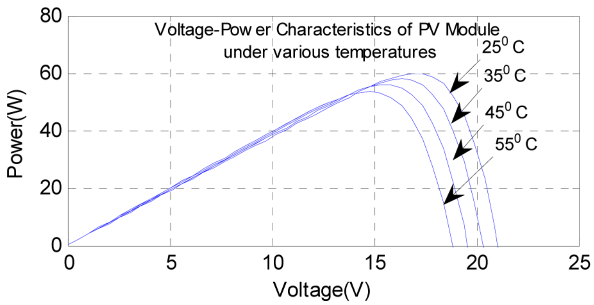


Figure 15. **(a)** Voltage-power characteristics of MSX 60 PV under various irradiation level at T=25 oC. (b) Voltage-Power characteristics of MSX 60 PV under various temperature level at G=1000W/m^2.

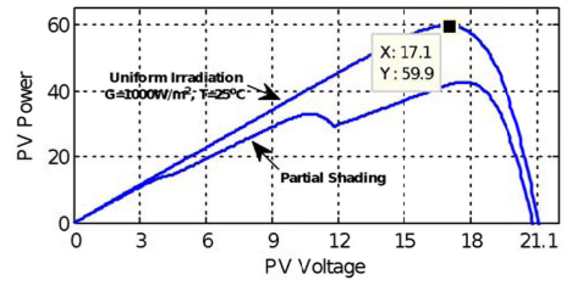
cells are set as G2 = 600 W/m^2. The V-P characteristics and V-I characteristics of MSX 60 PV for the selected cases is presented in Figure 17(a) and Figure 17(b) respectively.

The V-P characteristics shown in Figure 18(a) and I-V characteristics shown in Figure 18(b) are the simulation results obtained by setting G1=1000 W/m^2 for 24 cells and the remaining 12 cells in a PV modules is set with irradiation of G2 = 750 W/m^2

4.3 Partial Shading of PV String

The partial shading effect on PV modules in a PV string is analyzed by performing the simulation for PV string which has 3 series connected PV modules. Simulation model of PV string is shown in Figure 19.

Different irradiation values are applied to each of the modules by maintaining the temperature value as constant for all the 3 modules. The irradiation values applied to the modules are G(PV1) = 1000 W/m^2, G(PV2) = 600 W/m^2 and G(PV3) 750 W/m^2. Figure 20(a) shows the V-P characteristics of PV string under uniform irradiation



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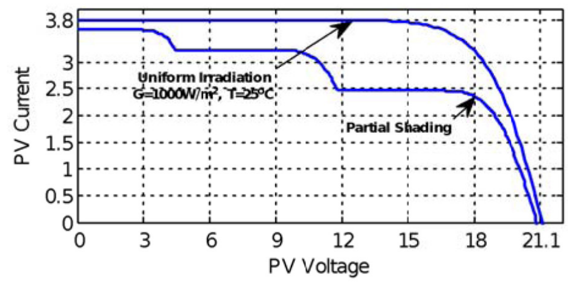
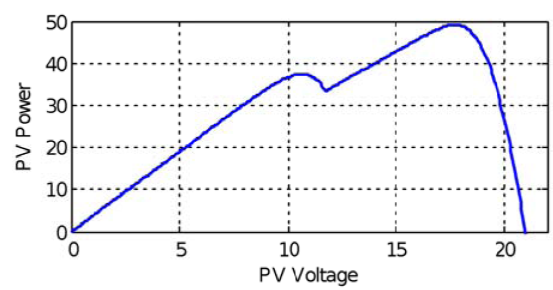


(b)

Figure 16. **(a)** V-P characteristics of PV module under partial shading. **(b)** V-I characteristics of PV module under partial shading.



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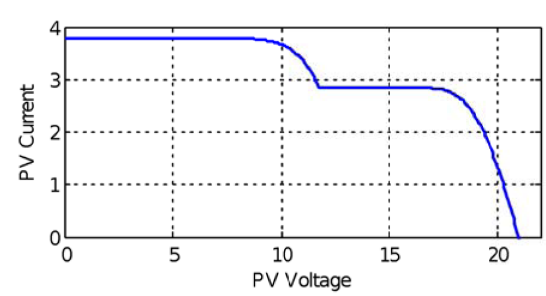
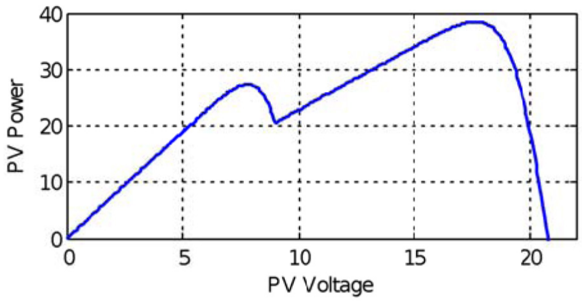


(b)

Figure 17. **(a)** V-P characteristics of PV module under partial shading. **(b)** V-I characteristics of PV module under partial shading.



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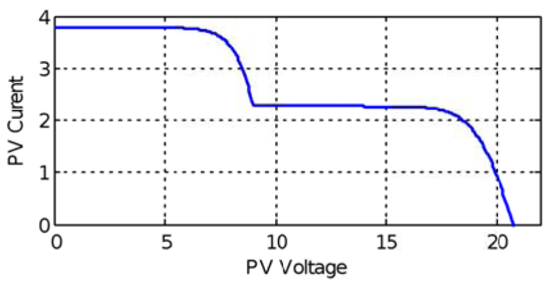


(b)

Figure 18. (**a**) V-P characteristics of PV module under partial shading. (**b**) V-I characteristics of PV module under partial shading.

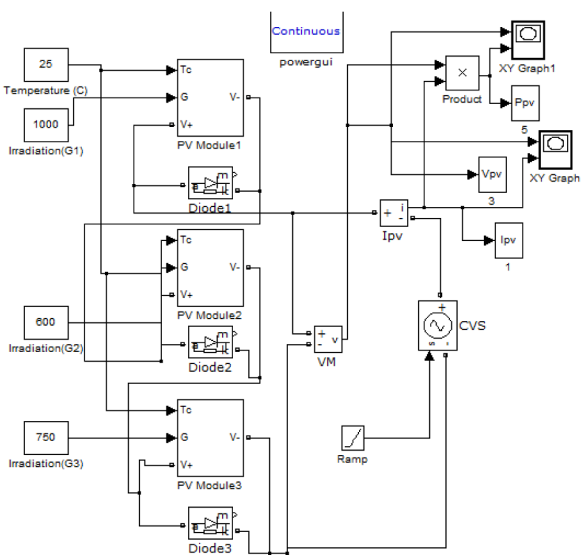
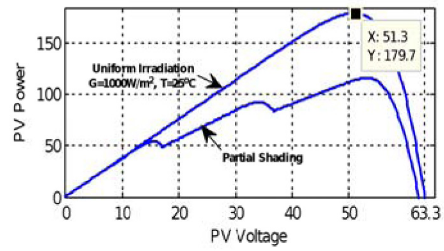
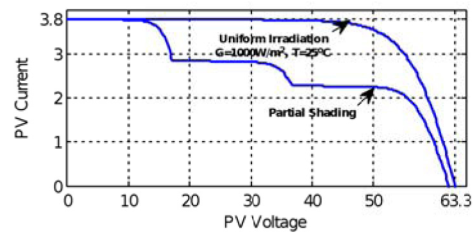


Figure 19. Simulation model of PV string.

and under partial shading conditions. For uniform irradiation of PV string G is maintained as 1000W/m^2 for all modules at the cell temperature of T_c = 25°C. At STC, the open circuit voltage of MSX 60 PV module is 17.1 V and



(a)



(b)

Figure 20. (**a**) V-P characteristics of PV string under partial shading. (**b**) V-I characteristics of PV module under partial shading.

the maximum power is 60W. The PV string has 3 modules connected in series

Therefore,

$$V_{oc} = 17.1 \text{ x } 3 = 51.3 \text{ V and}$$

$$P_{max} = 60 \text{ x } 3 = 180\text{W}.$$

The power obtained through simulation is 179.7 W. The obtained results are well matched with the data sheet information. This confirms the accuracy of the developed PV module.

I-V characteristics of PV string under uniform irradiation and the under partial shading conditions is shown in Figure 19(b).

5. Conclusion

Modeling simulation and analysis of PV modules under partial shading conditions is presented in this paper. Development of Photovoltaic module model based on the mathematical equations using MATLAB/Simulink is explained in detail. Simulation of PV module and PV string under uniform irradiation and partial shading are carried out for various conditions. The results obtained from the simulation are presented and discussed. The simulation results confirm the accuracy of the developed module model and hence, the model can be used to analyze the characteristics of any PV module, PV string or PV array under uniform irradiation and partial shading conditions.

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