RESEARCH ARTICLE OPEN ACCESS

Mathematical Modeling of Solar Photovoltaic Cell using MATLAB/Simulink and Study under Different Climatic Condition

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ABSTRACT
This paper describes step-by step modeling and simulation of solar photovoltaic (PV) single diode based equivalent model in MATLAB/Simulink. A PV module is built with number of solar cell connected in series-parallel combination. Initially, the I-V and P-V characteristics are mathematically derived for a single PV cell, and to end with, it is completed for the PV panel. The modeling of solar PV cell is done based on five parameters taken from the manufacturer's data sheet. The following PV model is accurately forecasting the open circuit voltage, short circuit current, I-V and P-V characteristics, and maximum power the various temperature and solar irradiation conditions. Further performance of PV module/array is analyzed by simulation results. Output effects by weather condition, irradiance and temperature, number of cell connected is series and parallel, series and parallel resistance are analyzed.

Keywords – MATLAB, modeling, PV Cell, I-V characteristics, P-V characteristics

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Date of Submission: 02-06-2023 Date of acceptance: 12-06-2023

I. INTRODUCTION

The rapid increase of use of solar energy in renewable energy sources, especially in distributed generation field; the PV power market is rapidly expanded. So, a reliable and flexible tool is essential to predict the power generation under different climatic condition. Researcher is updated PV model in day-by-day for a better understanding of the operation.

Depends on the various simulation software's such as MATLAB, Simulink, C-program, Sci-lab, LTSpice, etc., the developed PV model differs from each other. However, most of the mathematical models are developed based on the voltage (V) – current (I) relations. This I-V relation is the basis for all the PV cell modeling. The simplification to I-V relation is done by considering infinite shunt resistance. The utilization of the latest electric power control techniques called the Maximum Power Point Tracking (MPPT) techniques has moved to enhance the effectiveness of solar system operation modules. Therefore, predictions with respect to the physical structure of the cell behavior can be developed a mathematical model of the PV module.

In this research paper, step by step procedure has been defined for modeling solar cell, panel, and array models of the photovoltaic system. BP365TS, BP3230T and SPR-200-WHT-U solar panel are used as a reference model for further modeling. The PV array characteristic is simulated for different climatic condition; irradiance (1000 W/m2, 500 W/m2 and 200 W/m2) and temperature variation (25°C, 50℃ and 75°C). The output characteristic of the reference model matches with simulated results.

The paper is organized as follows: section 2 describes equivalent circuit of PV cell and section 3 explains the mathematical equation to describe the equivalent circuit of PV cell/module/array. Section 4 describes modeling of PV model in MATLAB/Simulink. The simulation results under different climatic conditions are discussed in section 5. Section 6 concludes the paper.

II. EQUIVALENT CIRCUIT FOR PV CELL AND ARRAY

The PV solar system is an interconnection of number of PV cells/module in series-parallel combination. The power developed by a single diode module is insufficient for large electric load, so such modules are interconnected to build up output for the load. The series interconnection is used to achieve required voltage and parallel interconnection is used to get sufficient value of current.

Considering a single solar cell (Figure 1); a PV module can be modeled by using a current source, a diode and two resistors. The equivalent circuit of PV cell is consist of Photo current (I_{ph}), diode, Series resistance (R_s) and Parallel resistance (R_p). The photo current is anti-parallel with diode. Also R_p and R_s connected in parallel and series respectively.

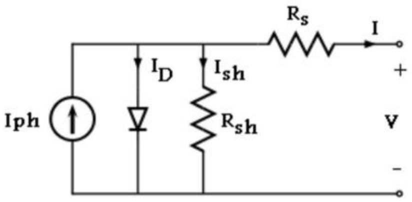


Fig -1: Equivalent circuit of PV cell [1]

Practically, PV cells are large grouped units called PV modules and these modules diodes are connected in series or parallel to create PV array which are used to generate electricity in PV generation systems. The equivalent circuit for PV array is shown in Fig. 2.

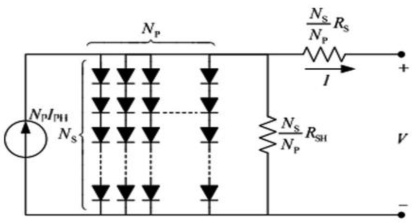


Fig -2: Equivalent circuit of solar array [1]

III. MATHEMATICAL MODELING OF SOLAR CELL IN MATLAB

For analysis, researchers need a reliable model to forecasts the PV power generated correctly when connected in series-parallel. Applying Kirchhoff's current law in the model shown in figure 1, the total PV current is presented in equation 1 [2].

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

Where Iph is the photocurrent, when the PV cell is visible to incident sunlight. The photocurrent is linearly varying concerning solar irradiance at a certain temperature. Id is an anti-parallel diode current, and it produces the non-linear response on the PV cell. The current flow through the shunt resistor is represented by Ish. Substitute the expression for Ish and Id in equation 1, and the PV current is derived in equation 2 [2].

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \frac{V+IR_S}{R_p} \quad (2)$$

Where q is electron charge = 1.6×10-19; n is ideality Factor = 1.2; k is Boltzmann constant = 1.3805×10-23 J/K; $V_d = V + IR_s$ and $V_t = \frac{nkT}{q}$; Io is the saturation current of the diode, the temperature of the PV cell is represented by T, R_p & R_s represents the shunt and series resistance, respectively. The photocurrent of the PV is depending on the irradiation and the cell temperature. The expression for the photocurrent is given in equation 3 [2].

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times \frac{I_r}{I_{r0}} \quad (3)$$

Where K_i is short-circuit current temperature coefficient of cell = 0.0024 and solar irradiation is represented as Ir_0 = 1000 W/m^2 at Standard Reference Condition. The module saturation current (I_0) varies with the cell temperature, which is given by equation 4 [2]

$$I_o = I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{q \times E_g}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad (4)$$

Where PV cell temperature is represented as T_r = 298 K or 25˚C and the band gap energy, represented by Eg, can expressed by equation 5 [3].

$$E_g = E_{g0} - \alpha\frac{T^2}{T+\beta} = 1.16 - 7.02 \times 10^{-4}\left[\frac{T^2}{T-1108}\right] \quad (5)$$

The modules reverse saturation current (I_{rs}) can be expressed by equation 6 [4].

$$I_{rs} = \frac{I_{sc}}{e^{\frac{q(V+IR_S)}{nkT}} - 1} \quad (6)$$

In order to enhance the ability of electric power generation from solar PV systems, the solar cells should be implemented in series and shunt combinations. If Np represents the cells interconnected in parallel and Ns shows the cells interconnected in series, the relationship between the output current and voltage is presented as follows [2,5]

$$I = N_p \times I_{ph} - N_p \times I_0 \times \left[exp\left(\frac{V/N_s + I \times R_s/N_p}{n \times V_t}\right)\right] - I_{sh} \quad (7)$$

$$I_{sh} = \frac{V \times N_p/N_s + I \times R_s}{R_P} \quad (8)$$

IV. MODELING OF SOLAR CELL IN MATLAB

The complete PV module, designed and simulated in MATLAB/Simulink R2015a is shown in figure 3. Solar irradiance (Ir) and temperature (T) is taken as input variables and the power generated by PV module is taken as output in form of current (I) and voltage (V).

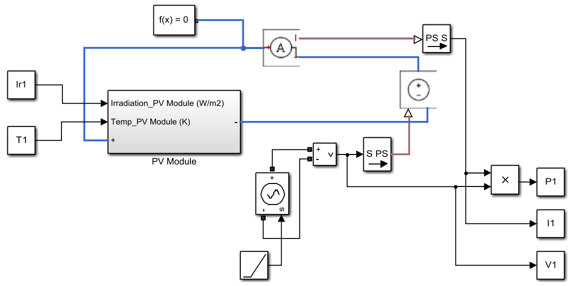


Fig -3: Implementation Modelling of Complete PV module

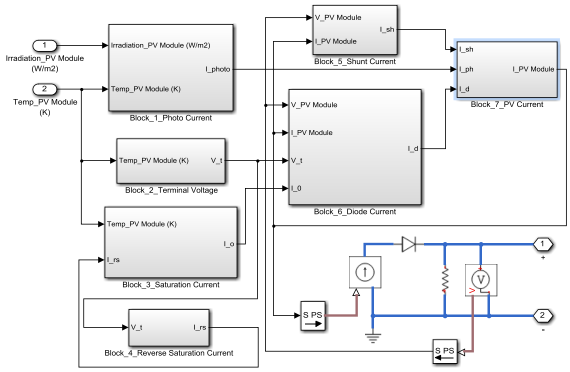


Fig -4: Subsystems of the complete PV Module

The whole simulation model is compressed in single block model and is represented in figure 3, whereas figure 4 represents the grouped subsystems of complete model to make the understanding easier. It is divided into seven subsystems or blocks. Equation 3, 4, 6 and 8 are modeled in these for blocks.

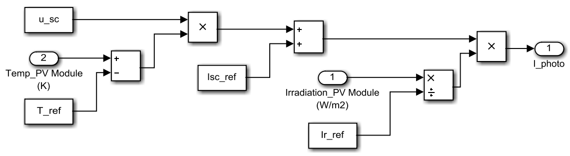


Fig -5: Implementation Modelling of I_{ph} (Block 1)

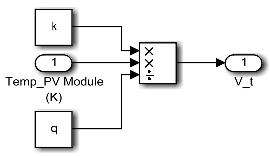


Fig -6: Implementation Modelling of V_t (Block 2)

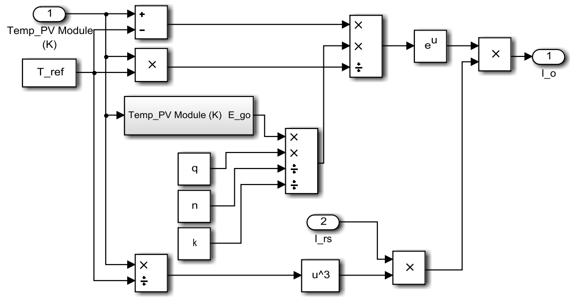


Fig -7: Implementation Modelling of I_0 (Block 3)

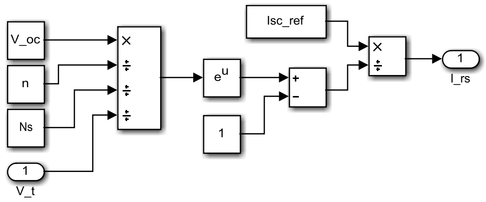


Fig -8: Implementation Modelling of I_{rs} (Block 4)

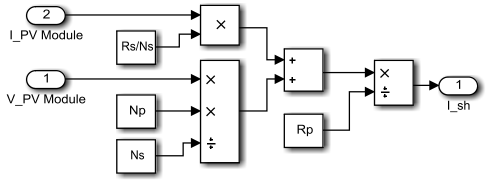


Fig -9: Implementation Modelling of I_{sh} (Block 5)

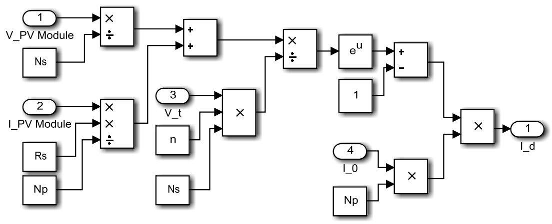


Fig -10: Implementation Modelling of I_d (Block 6)

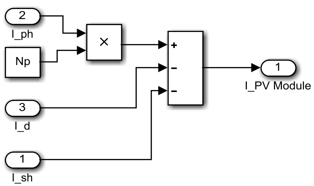


Fig -11: Implementation Modelling of I_d (Block 7)

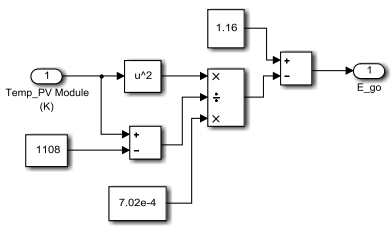


Fig -12: Implementation Modelling of E_g

V. RESULT AND DISCUSSION

In MATLAB/Simulink the PV model is developed using the equations (1-8). The simulation is done for three different rating panels with the data given by the panel manufacturers for different irradiation and temperature conditions. The selected panel are BP Solar BP365TS, BP Solar BP3230T, and SunPower SPR-200-WHT-U. The model physical parameters are taken from the datasheet of the module are listed in Table 1 [3].

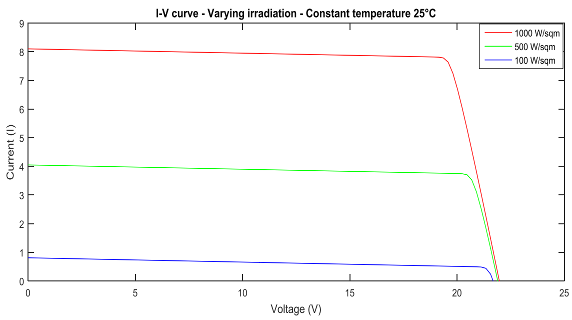
Table -1: Reference parameters of the PV model

Parameters	BP Solar BP365TS	BP Solar BP3230T	SunPower SPR-200-WHT-U
V_{oc} (V)	11	36.4	47.8
I_{sc} (A)	8.1	8.4	5.4
R_P (Ω)	0.13134	0.41305	0.4427
R_S (Ω)	49.95	179.89	232.82
n	0.9768	0.9624	0.96675

Figure 13 shows the I-V and P-V characteristics for BP Solar BP365TS module at 25˚C constant cell temperature and the various solar irradiations: 1000 W/m^2; 500 W/m^2; 100 W/m^2. From I-V characteristics, it is observed that I_{sc} and V_{oc} are almost the same as that of the real values. The calculated error for V_{MPP}, I_{MPP} and P_{max} are tabulated in table 2. the values of the VMPP,IMPP and PMAX according to the reference value is given. The error between the reference and Simulink is so small that it can be negligible.

Table -2: Comparison of simulation result with datasheet for model BP365TS at 1000 W/m^2 on 25˚C

	Reference Value	Simulink Value	Error (%)
V_{MPP}	8.7	8.69	0.11
I_{MPP}	7.5	7.48	0.25
P_{MPP}	65	65.01	0.015



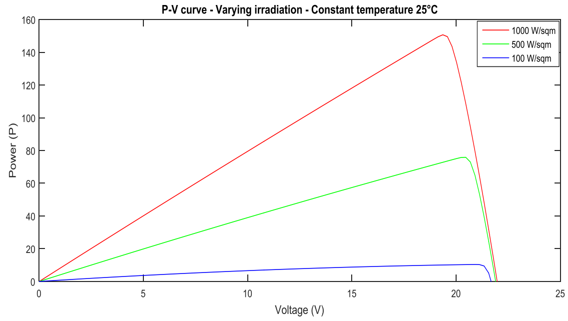


Fig -13: I-V and P-V characteristics for BP Solar BP365TS PV panel at 25˚C constant temperature

Figure 14 and 15 shows I-V and P-V characteristics for BP Solar BP3230T and SPR-200-WHT-U module respectively at 25˚C constant cell temperature and the various solar irradiations: 1000 W/m^2; 500 W/m^2; 100 W/m^2. Upon analyzing the data, we can conclude that as the irradiation increases, there is a corresponding increase in the current and voltage output of the model. Consequently, this leads to an overall enhancement in the power output during these operating conditions.

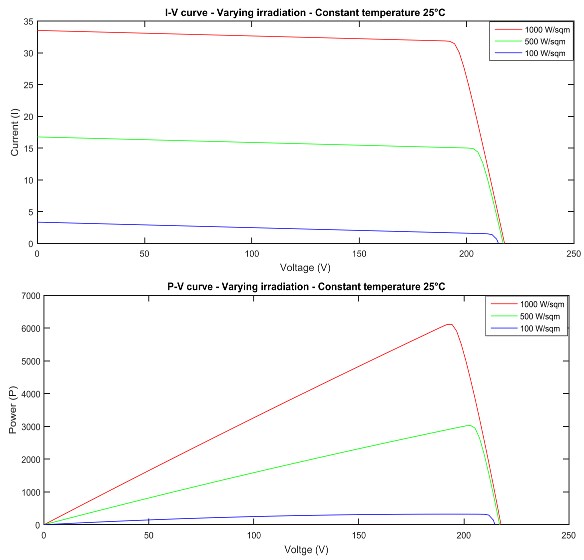
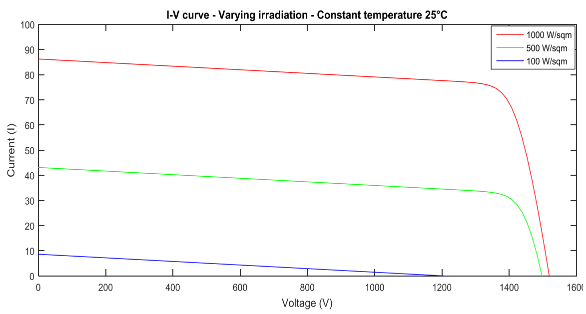


Fig -14: I-V and P-V characteristics for BP Solar Model No BP3230T PV panel at 25˚C constant temperature



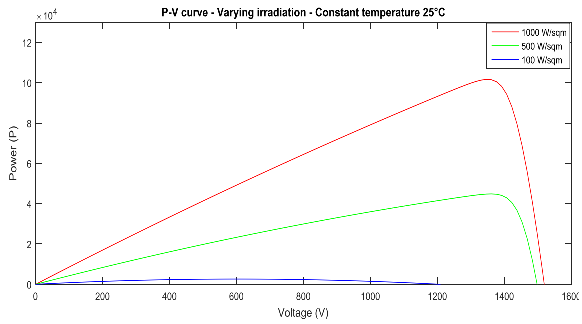


Fig -15: I-V and P-V characteristics for Model No SPR-200-WHT-U PV panel at 25˚C constant temperature

Figure 16 shows I-V and P-V characteristics for Solar module BP365TS with 1000 W/m^2 constant irradiation and various temperature at 25˚C, 50˚C and 75˚C.With the operating temperature increases, there is a slight increase in the current output, but a significant decrease in the voltage output. Consequently, the overall power output experiences a noticeable decline as the temperature rises.

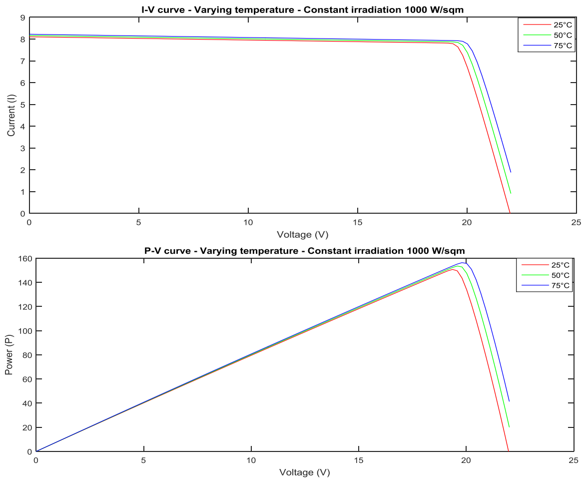


Fig -16: I-V and P-V characteristics for BP Solar BP365TS PV panel with 1000 W/m^2 constant irradiation

The error in simulation for V_{MPP}, I_{MPP} and P_{max} are tabulated in table 3 and 4 respectively for BP Solar BP3230T and SPR-200-WHT-U module.

Table -3: Comparison of simulation result with datasheet for model BP3230T at 1000 W/m^2 on 25˚C

	Reference Value	**Simulink Value**	**Error (%)**	**Reference Value**	**Simulink Value**	**Error (%)**
	for model BP3230T			**for PR-200-WHT-U module**		
V_{MPP}	29.1	31.3	7.56	40	41.59	3.975
I_{MPP}	7.9	7.34	6.89	5	4.76	4.76
P_{MAX}	230	230.2	0.08	200	198	1

Figure 17 and 18 shows I-V and P-V characteristics for BP Solar BP3230T and SPR-200-WHT-U module respectively with 1000 W/m^2 constant irradiation and various temperatures at 25˚C, 50˚C and 75˚C.

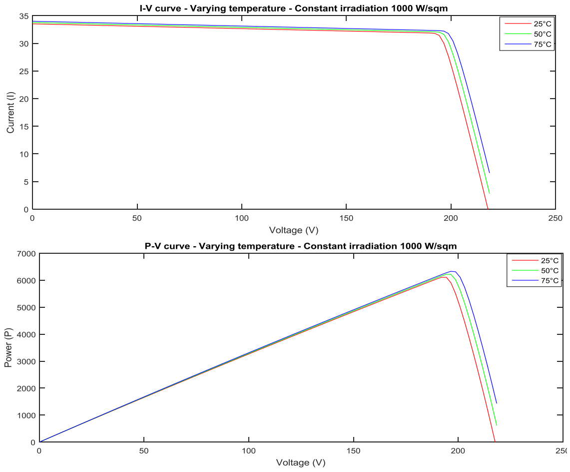


Fig -17: I-V and P-V characteristics for BP Solar BP3230T PV panel with 1000 W/m^2 constant irradiation

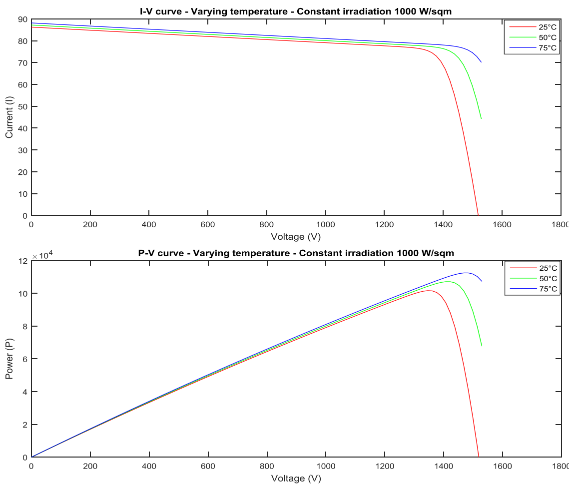


Fig -18: I-V and P-V characteristics for Model No SPR-200-WHT-U PV panel with 1000 W/m^2 constant irradiation

The maximum power observed in simulation comparison with model datasheet with irradiation value 1000 W/m^2, 750 W/m^2, 500 W/m^2 and 250 W/m^2 on 25˚C are tabulated in table 4, 5 and 6 respectively for BP Solar BP365TS, BP Solar BP3230T, and SunPower SPR-200-WHT-U.

Table -4: Comparison of simulation result (P_{MAX}) with datasheet for model BP365TS on 25˚C

Irradiation Value	**Reference Value**	**Simulink Value**	**Error (%)**
1000	64.94	72.42	11.57
750	51.12	54.07	5.77
500	33.95	34.74	2.3
250	17.95	14.47	19.38

Table -5: Comparison of simulation result (P_{MAX}) with datasheet for model BP3230T on 25˚C

Irradiation Value	Reference Value	Simulink Value	Error (%)
1000	230	250.1	8.73
750	175.8	187.5	6.65
500	116.5	121.4	10.04
250	59	52.07	11.74

Table -6: Comparison of simulation result (P_{MAX}) with datasheet for model SPR-200-WHT-U on 25˚C

Irradiation Value	Reference Value	Simulink Value	Error (%)
1000	200	207.94	3.97
750	152.4	158.36	3.91
500	102.6	110.10	3.91
250	48.2	53.7	11.41

The effect of change in combination of N_s and N_p with irradiation & temperature keep constant at 1000 W/m^2 and 25˚C is also simulated. The I-V and P-V characteristics are shown in figure 19, 20 and 21.

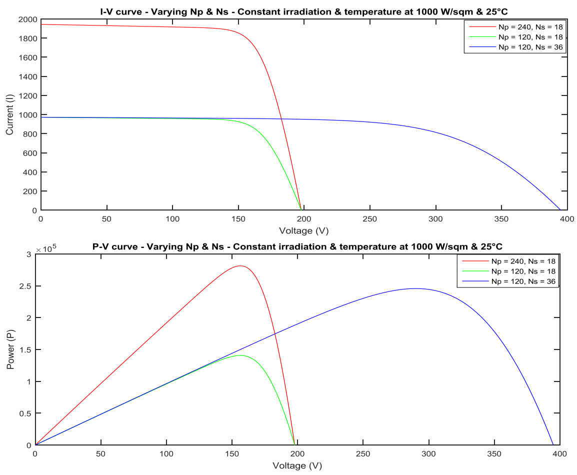
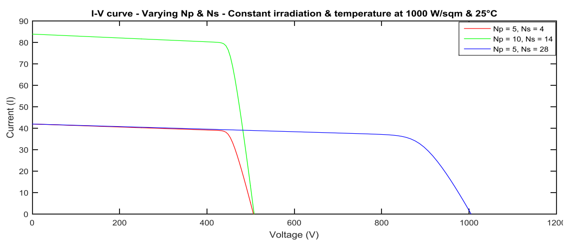


Fig -19: I-V and P-V characteristics for BP Solar BP365TS PV panel with different combination of N_p & N_s



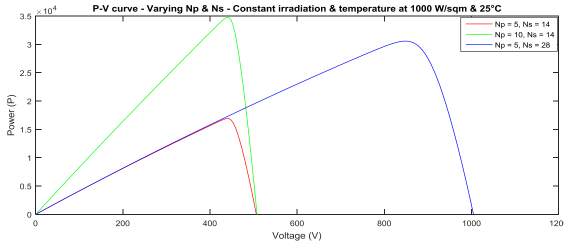


Fig -20: I-V and P-V characteristics for BP Solar BP3230T PV panel with different combination of N_p & N_s

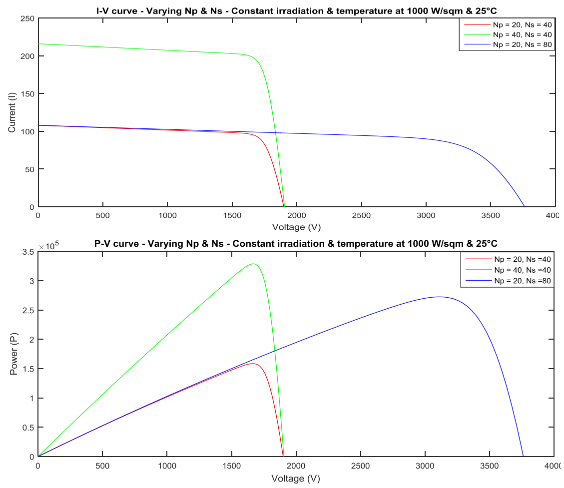


Fig -21: I-V and P-V characteristics for SPR-200-WHT-U PV panel with different combination of N_p and N_s

In practice, PV cells are connected in series-parallel combination to form PV array for generating more electricity from sunlight. It has been observed that when N_p is increase then current is increase and when N_s is increase the voltage is increase.

VI. CONCLUSIONS

Stepwise procedure for modeling solar panel and array in MATLAB with user-friendly stimulation tool is shown in each step, which will help further modeling the solar system and I-V & P-V characteristic. The efficiency of the models is much near to the reference value and here also shows that with varying irradiation, temperature, series resistance, parallel resistance, N_p and N_s and their effects on the 3 models.

The present model is the dynamic model for further modeling solar PV systems so that any system behavior can be predicted for any number of cells, panel, or array under any variable of environmental condition like temperature, irradiance, series resistance, shunt resistance, etc. for its performance analysis in power generation application in a solar PV system.

REFERENCES

[1]. Salmi, T., Bouzguenda, M., Gastli, A. and Masmoudi, A., 2012. Matlab/simulink based modeling of photovoltaic cell. International journal of renewable energy research, 2(2), pp.213-218.

[2]. Prakash, R. and Singh, S., 2016. Designing and modelling of solar photovoltaic cell and array. IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), 11(2), pp.35-40.

[3]. Premkumar, M., Chandrasekaran, K. and Sowmya, R., 2020. Mathematical modelling of solar photovoltaic cell/panel/array based on the physical parameters from the manufacturer's datasheet. International Journal of Renewable energy development, 9(1), p.7.

[4]. Nguyen, X.H. and Nguyen, M.P., 2015. Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink. Environmental Systems Research, 4, pp.1-13.

[5]. Chenni, R., Makhlouf, M., Kerbache, T. and Bouzid, A., 2007. A detailed modeling method for photovoltaic cells. Energy, 32(9), pp.1724-1730.