

Modelling and Simulation of Photovoltaic Array Using Matlab/Simulink

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Abstract - Photovoltaic power supplied to the utility grid is gaining more and more visibility while the world's powers demand increases. In this paper we are defining a circuit-based simulation model for a PV cell in order to estimate the electrical behavior of the cell with respect to changes in environmental parameters such as temperature and irradiance. The PV system requires many special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell operating temperature of PV arrays. PV cell is the most basic element of photovoltaic generation units, which converts the solar energy into electrical energy. This paper focuses on a MATLAB/Simulink model of a photovoltaic cell. This model is based on mathematical equations and is described through an equivalent circuit including a photocurrent source, a diode and a series resistor. The developed model allows the prediction of PV cell behavior under different physical and environmental parameters. In addition, this paper outlines the working principle of PV module as well as PV array. So this completed model accepts irradiance and temperature as variable parameters and outputs the I-V as well as P-V characteristic. In order to validate the developed model, the simulation results are compared with the standard results and characteristic curves provided by the PV array manufacturer and they show excellent resemblance.

Key words - PV cell characteristics, modeling of PV module, validation.

I. INTRODUCTION

The development of new energy sources is continuously enhanced because of the critical situation of the chemical industrial fuels such as oil, gas and others. Thus, the renewable energy sources have become a more important contributor to the total energy consumed in the world. Among the renewable energy resources, the energy through the photovoltaic (PV) effect can be considered the most essential resource. In spite of the irregularity of sunlight, solar energy is widely available and completely free of cost.

The focus of this paper is on solar cell modeling. This paper carried out a MATLAB/Simulink model of PV cell behavior under different varying parameters such as solar radiation, ambient temperature, series resistor, shunt resistor, etc. Then the simulation results obtained are also compared with the standard results provided by the manufacturer. This model can be used to get characteristic curves of any type of PV array under different environmental conditions.

II. CHARACTERISTICS OF PV CELL

The electrical characteristic of the PV cell is generally represented by the current versus voltage (I-V) curve. Figure 1 shows the I-V characteristic of a PV module.

The top left of the I-V curve at zero voltage is called the short-circuit current. This current is measured with the output terminals shorted (zero voltage). The bottom right of the curve at zero current is called the open-circuit voltage. This voltage is measured with the output terminals open (zero current).

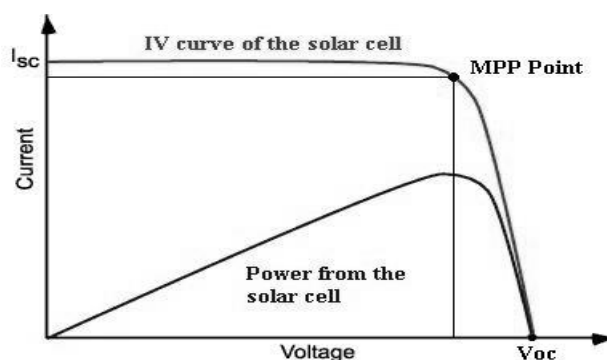


Figure 1: Characteristics of a PV Cell

In the left region, the cell works like a constant current source, generating voltage to match with the load resistance. In the right region, the current drops rapidly with a small rise in voltage. In this region, the cell works like a constant voltage source with an internal resistance. Somewhere in the middle of the two regions, the curve has a knee point.

III. MATHEMATICAL MODEL OF PV CELL

The equivalent electrical circuit shown in figure 2 can represent the complex physics of the PV cell.

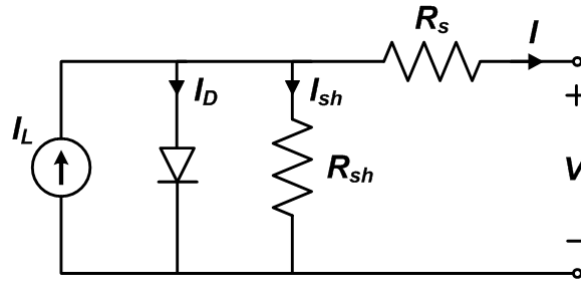


Figure 2: Equivalent Electrical Circuit of a PV Cell

The circuit parameters are as follows.

- The output-terminal current I is equal to the light-generated current I_L , less the diode-current I_d and the shunt-leakage current I_{sh} .
- The series resistance R_s represents the internal resistance to the current flow, and depends on the p-n junction depth, the impurities and the contact resistance.
- The shunt resistance R_{sh} is inversely related with leakage current to the ground.

In an ideal PV cell, $R_s = 0$ (no series loss), and $R_{sh} = \infty$ (no leakage to ground). In a typical high quality one square inch silicon cell, $R_s = 0.05$ to 0.10 ohm and $R_{sh} = 200$ to 300 ohms. The PV conversion efficiency is sensitive to small variations in R_s , but is insensitive to variations in R_{sh} . Therefore, we can ignore R_{sh} from the equivalent electrical circuit for our modelling.

In the equivalent circuit, the current delivered to the external load equals the current I_L generated by the illumination, less the diode current I_d .

$$I = I_L - I_o \left(e^{\frac{q(V+IR_s)}{nkT_r}} - 1 \right) \quad (1)$$

where

- I_L is the current generated by solar cell (A)
- I_o is the diode saturation current (A)
- q is the electron charge = 1.6×10^{-19} Coulomb
- n is the ideality factor of diode which varies from 1 to 2
- k is Boltzmann constant = 1.38×10^{-38} Joule/Kelvin
- T_r is the rated cell temperature (K)

The cell could be represented by a voltage-current equation:

$$V = V_{sh} - R_s I \quad (2)$$

where

- V is the cell output voltage (V)
- I is the load (cell) output current (A)
- V_{sh} is the voltage across shunt resistance (V)

A MATLAB/Simulink model is made based on equations (1) & (2) as shown in fig. 3.

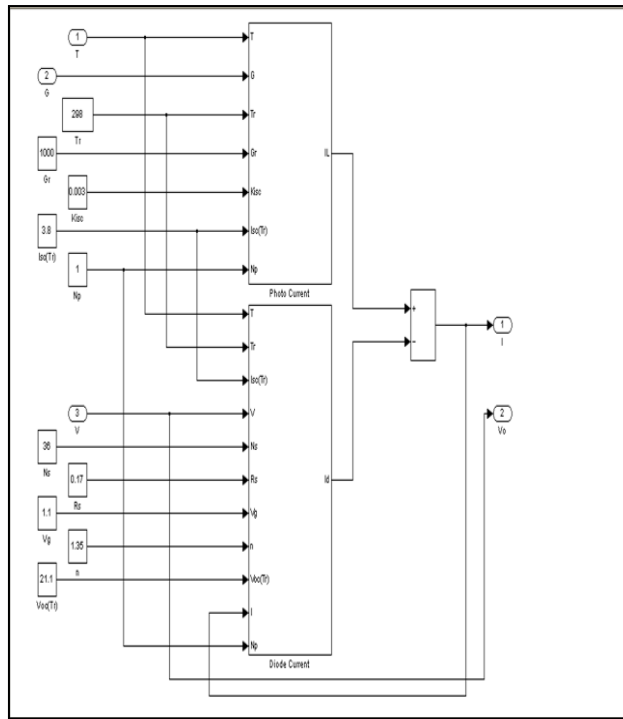


Figure 3: PV Cell MATLAB/Simulink Model

IV. EFFECT OF SOLAR RADIATION VARIATION

The model shown in fig. 3 consists of two subsystems, one of them is photocurrent. The photocurrent depends on the radiation and the temperature according to equation (3).

$$I_L = G \times \frac{I_{sc}(T_r)}{G_r} \left(1 + \alpha_{I_{sc}}(T - T_r) \right) \quad (3)$$

Where

- $\alpha_{I_{sc}}$ is the short circuit temperature coefficient (A/°C)
- G is operating solar radiation level (W/m²)
- G_r is rated solar radiation level (W/m²)

Based on the equation (3), the subsystem of Fig. 4 is obtained.

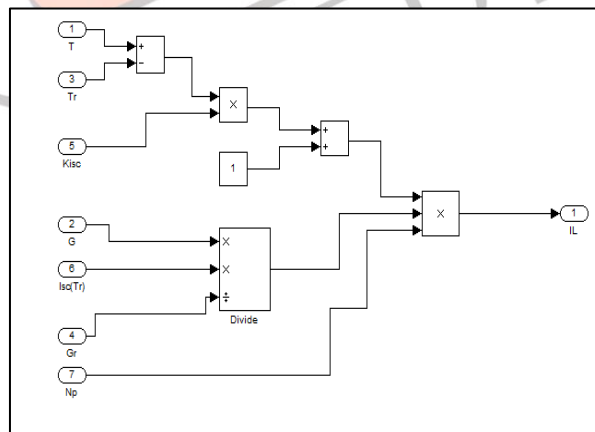


Figure 4: Subsystem of Photocurrent

V. EFFECT OF VARIATION IN CELL TEMPERATURE

The diode reverse saturation current I_o in equation (1) varies as a cubic function of the temperature and it can be expressed as:

$$I_o = I_o(T_r) \times \left(\frac{T}{T_r} \right)^3 \times e^{\frac{qV_g}{nk} \times \left(\frac{1}{T_r} - \frac{1}{T} \right)} \quad (4)$$

$$I_o(T_r) = \frac{I_{sc}(T_r)}{e^{\left(\frac{qV_{oc}(T_r)}{nkT} \right) - 1}} \quad (5)$$

Where

- $I_{sc(T_r)}$ is the short circuit current of the cell at rated temperature (A)
- V_g is the band gap voltage (V)
- $V_{oc(T_r)}$ is the open circuit voltage of the cell at rated temperature (V)
- T is operating temperature of the cell(K)

The other subsystem of the model shown in fig. 3 is Diode current, which contains a subsystem of diode reverse saturation current as shown in fig. 5.

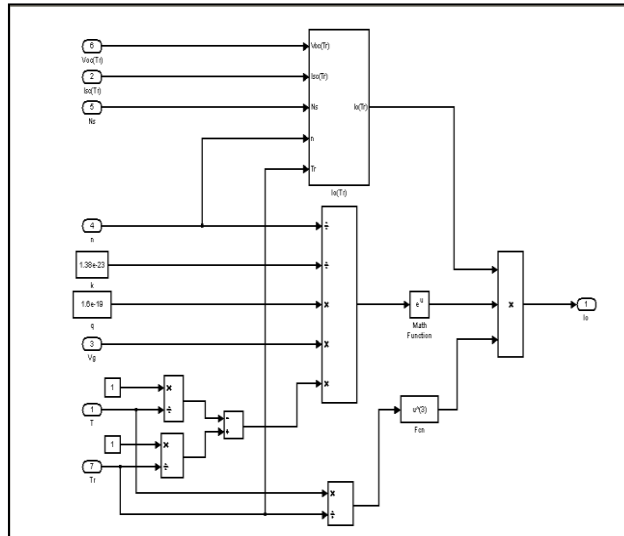


Figure 5: Subsystem of Reverse Saturation Current

VI. MATHEMATICAL MODEL OF PV ARRAY

Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series-parallel configuration on a module to produce enough high power. A PV array is a group of several PV modules, which are electrically connected in series and parallel circuits to generate the required current and voltage. The equivalent circuit for the solar module arranged in N_p parallel and N_s series is shown in Fig. 6.

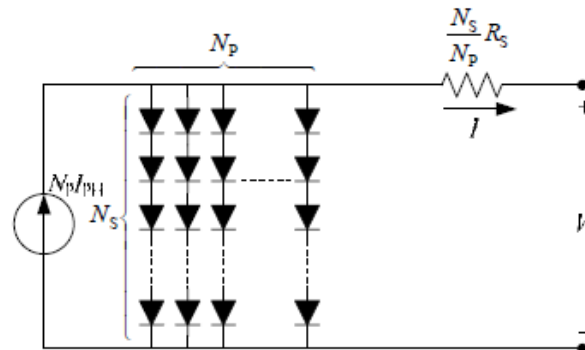


Figure 6: Equivalent Electrical Circuit of PV Array

Therefore, for the PV array, as shown in fig. 6, we can write output current equation as given below:

$$I = N_p I_{ph} - N_p I_d \tag{6}$$

Now for an array containing N_s cells in series and such N_p strings in parallel as shown in fig. 6, we can modify the diode current equations of the cell as presented below:

$$I_d = I_o \left(e^{\frac{q(V+I R_s)}{nkT_r N_s}} - 1 \right) \tag{7}$$

$$I_o = I_o(T_r) \times \left(\frac{T}{T_r} \right)^3 \times e^{\frac{qV_g}{nk} \times \left(\frac{1}{T_r} - \frac{1}{T} \right)} \tag{8}$$

$$I_o(T_r) = \frac{I_{sc}(T_r)}{e^{\left(\frac{qV_{oc}(T_r)}{nkT_r N_s} \right) - 1}} \tag{9}$$

VII. SIMULATION MODEL OF PV ARRAY

MATLAB/Simulink is used for the modelling task. The model is flexible for any number of modules connected in series and/or parallel branches in an array.

A Solarex MSX PV type is chosen for PV array modelling. This type is well suited for virtually all applications where PV System are feasible energy source, including pumping and irrigation, aids to navigation. The MSX60 module has 60W of rated power and 36 series connected polycrystalline silicon cells. The performance of typical MSX60 module is described by the electrical characteristics parameters given in below table 1.

The MATLAB/Simulink model is developed for a general PV array based on manufacturer data and from the mathematical equations, the output presents the PV array operating current.

After including all the equation explained above, we have a model that has a subsystem of PV array and inputs of environmental factors. Here, we have applied a ramp input for PV output voltage to produce the complete I-V and P-V graph.

Table 1: Key Specifications of the Solarex MSX60 PV Module

Description	Value
Peak Power (W)	60
Open circuit- V_{OC} (V)	21.10
Short-circuit current- I_{SC} (A)	3.8
Reference Irradiance- G_r (W/m^2)	1000
Reference Temperature- T_r (K)	298
Number of cell in series- N_s	36
Number of cell in parallel- N_p	1
Series resistance (Ω)	0.17
Ideality factor-n	1.35
Short circuit temperature coefficient- K_{isc} (A/K)	0.003
Bandgap Energy- V_g (eV)	1.1

Now we can get different output characteristics at different temperature and radiation levels by just changing the value of input parameters T and G.

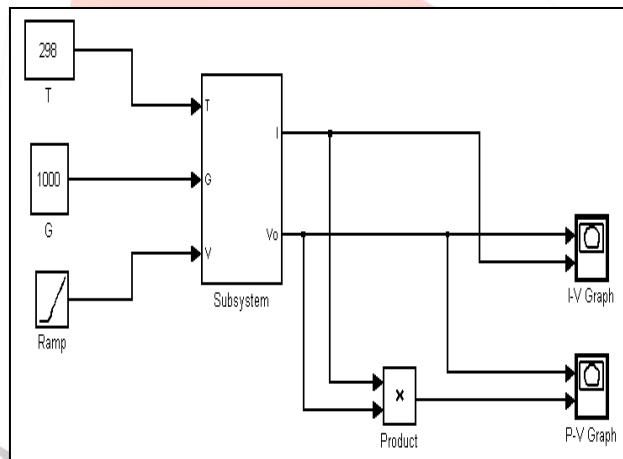


Figure 7: Simulink model of PV array

VIII. VALIDATION OF PROPOSED MODEL

The proposed model can provide calculated current, voltage and power relationships for different environmental conditions of solar radiations and ambient temperatures. These I-V and P-V characteristics are produced by the proposed model for chosen PV array type through MATLAB/Simulink environment. The validation of results are done in three steps:

- Validation under standard test conditions - The waveforms are produced for Standard Test Conditions (STC) of full sun radiation ($1000W/m^2$) and 298K temperature. A commercial software package (PVSystem) is used to present the I-V and P-V characteristics for the same type from large database built in it. These characteristics developed by PVSystem are compared with the ones obtained from Simulink model.

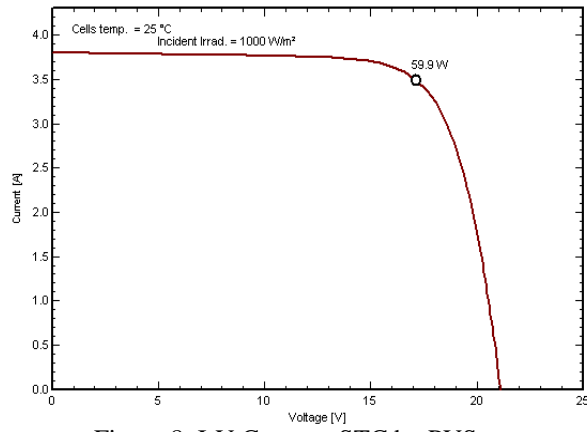


Figure 8: I-V Curve at STC by PVSyst

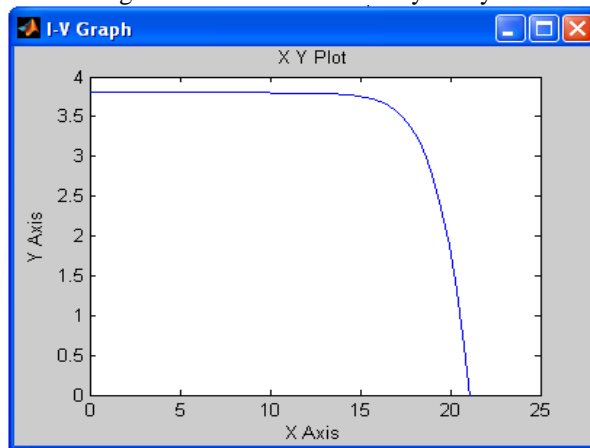


Figure 9: I-V Curve at STC by Simulation

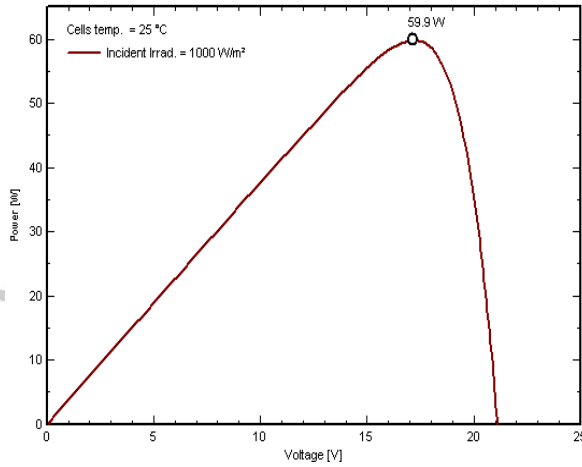


Figure 10: P-V Curve at STC by PVSyst

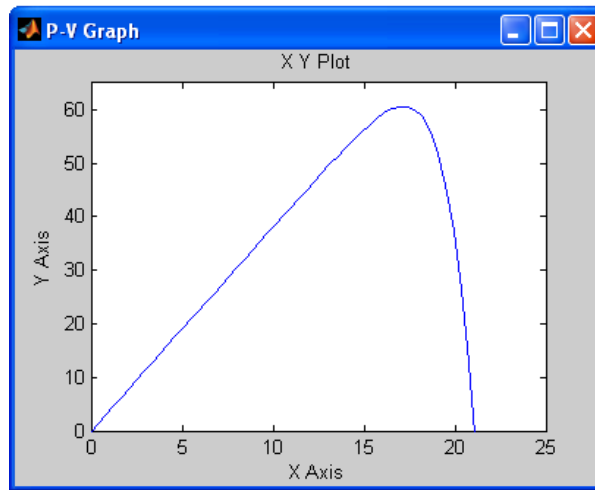


Figure 11: P-V Curve at STC by Simulation

- Validation under different temperature levels - To assure the flexibility and accuracy of the developed Simulink model, the model is tested under different temperature levels. These I-V and P-V characteristics are developed at 1000W/m² and 313 K from the manufacturer's datasheet in PVSyst software and the proposed Simulink model.

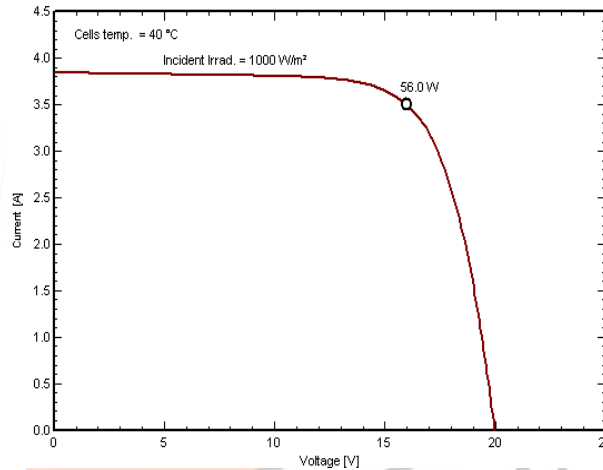


Figure 12: I-V Curve at 313K by PVSyst

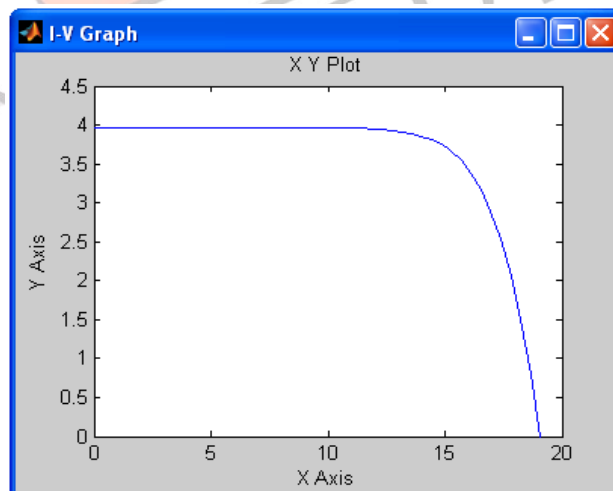


Figure 13: I-V Curve at 313K by Simulation

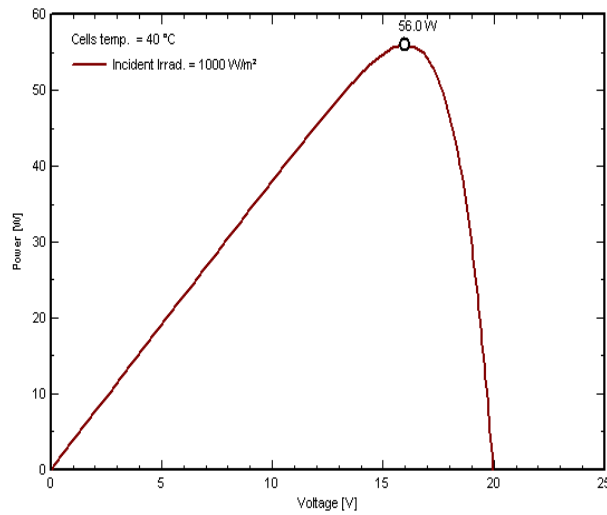


Figure 14: P-V Curve at 313K by PVSyst

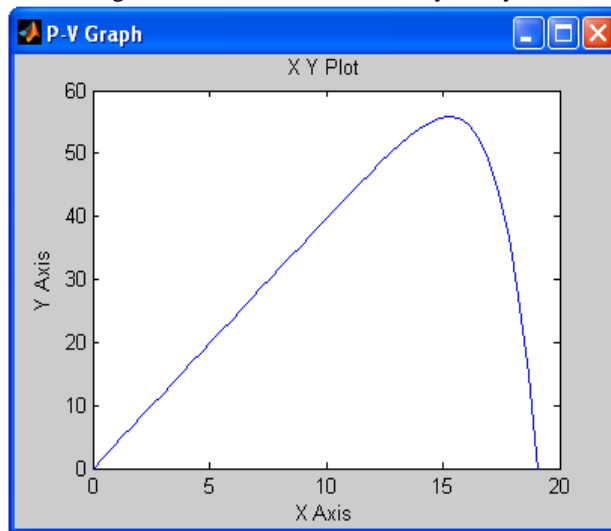


Figure 15: P-V Curve at 313K by Simulation

- Validation under different solar radiation levels - To further show capability of developed Simulink model to operate, not only at different temperatures, but also for different solar radiation levels, the model is simulated under different radiation level and results are compared to assure the accuracy. The simulations results using the developed Simulink model for radiation level 600 W/m² are compared with PVSyst results.

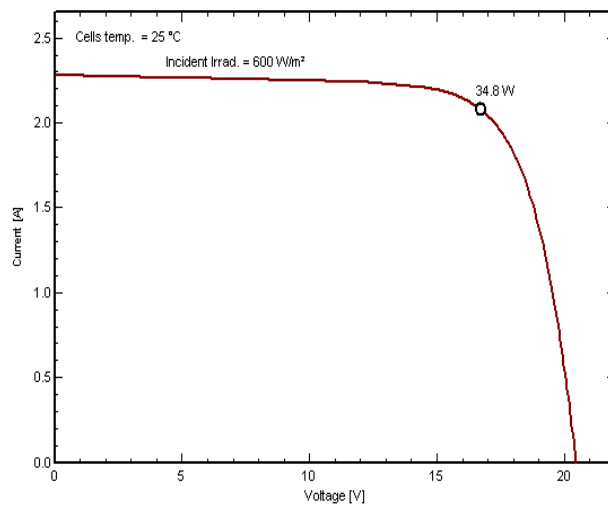


Figure 16: I-V Curve at 600 W/m² by PVSyst

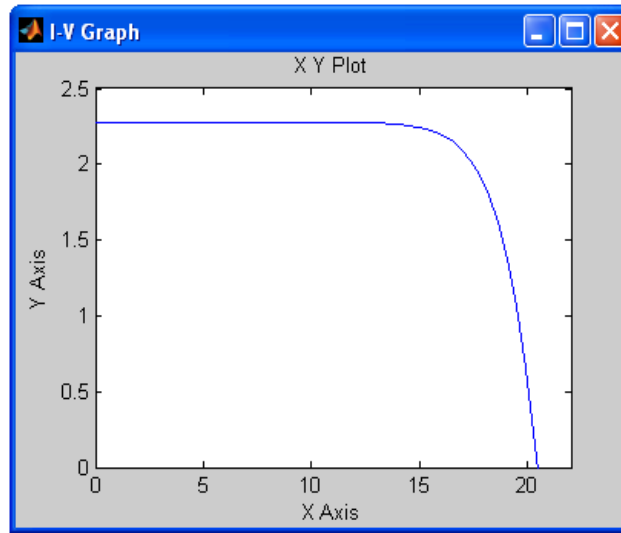


Figure 17: I-V Curve at 600 W/m2 by Simulation

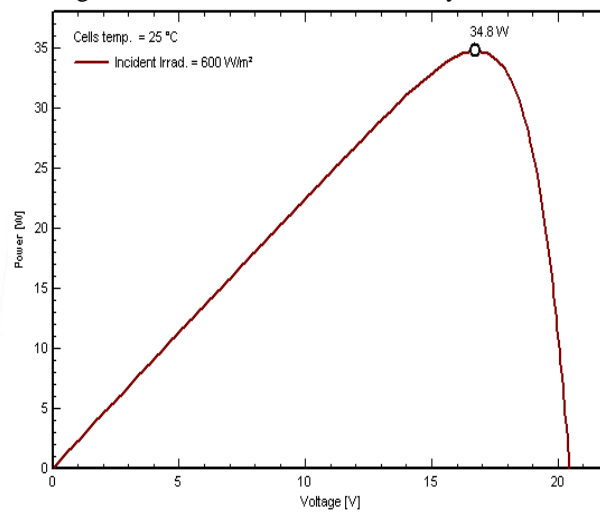


Figure 18: P-V Curve at 600 W/m2 by PVSystem

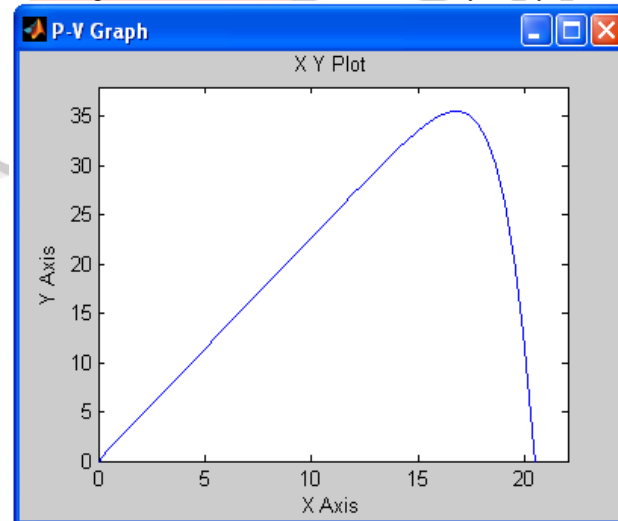


Figure 19: P-V Curve at 600 W/m2 by Simulation

IX. CONCLUSION

A mathematical model can be built using MATLAB/Simulink for PV array using appropriate equations for that. After comparing the results of industrial module and the proposed model, we can say that the results obtained by this method are very near to authentic in different environmental conditions. Therefore, we can conclude that the proposed model can predict the behaviour of any solar PV cell, module and array under climate and physical parameters changes.

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