SIMULATION OF PHOTOVOLTAIC ARRAY USING MATLAB / SIMULINK: ANALYSIS, COMPARISON & RESULTS

Anwarul M Haque[1], Swati Sharma[2], Devendra Nagal[3]
[1]Asst. Prof.,Power Electronics Department, VGEC Chandkheda, Ahmedabad, Gujarat, India,
[2,3]Asst. Prof, Electrical Engineering Department, Jodhpur National University,
Jodhpur, Rajasthan, India,
Email: haqueanwarul@yahoo.co.in[1], er.swati.sharma15@gmail.com[2], devendranagal@gmail.com[3]

Abstract— solar energy maintains life on earth and it is an infinite source of clean energy. Since last five decades, numerous studies have been performed on different design aspects and performance characteristics of Photovoltaic (PV) cells with a common objective of producing fully integrated PV modules to compete with the traditional energy sources. There is an increasing trend for the use of solar cells in industry and domestic appliances because solar energy is expected to play substantial role in future smart grid as distributed renewable source. This reviews the generalized optimization of mathematical modelling and simulation of Solar Photovoltaic System. The location of the power point maximal is unknown, for that purpose we use PV model, PV module and PV array simulation to sustain the PV array functioning spot at the Maximum Power Point (MPP). Here single diode equivalent circuit is employed in order to explore I-V and P-V characteristics of a 170W, BP 3170 module made of 72 solar cells (silicon nitride multi-crystalline) in series, using MATLAB/Simulink.

Index Terms—PV array, Simulation, Solar cell working and characteristics, Standard Test Conditions.

I. INTRODUCTION

The need for a cleaner environment and the continuous increase in energy demand, makes decentralized renewable energy production more and more significant. Solar cells, come in many different shapes and sizes and are made of electricity - producing materials. When sunlight shines on a PV cell, the absorbed light generates electricity. The mono-crystalline and poly-crystalline silicon cells are the only found at commercial scale at present era. To model a solar cell, it is imperative to assess the effect of different factors on the solar panels and to consider the characteristics given by the manufacturers in the datasheet [10].

The datasheet which gives the electrical characteristics is calculated under standard test condition. The PV array is composed of several interconnected photovoltaic modules. To obtain the required power, voltage and current, the PV modules are associated in series and parallel. Thus, the mathematical models for PV array are attained while utilizing the basic description and equivalent circuit of the PV cells.

From the theory of the photovoltaic, a mathematic model of the PV is presented. The simulation of the photovoltaic array is realized with SIMULINK block. The temperature and the irradiance are specified. The Simulink model uses a current source, voltage source and the value of the resistance in series and parallel of the PV. The number of modules in series and parallel are set. The result is used for the

Simulink block as a current source to obtain the voltage and current delivered from PV.

II. STANDARD TEST CONDITIONS (STC)

Uniform conditions are usually specified so that a performance comparison can be made between different PV units (cell, modules). The parameters obtained from the testing are usually provided on the manufacturer's datasheet. Measurements are performed under standard test conditions and the electrical characteristics obtained characterize the module accurately under these conditions. The conditions are specified as follows [1].

- The reference vertical irradiance E_o with a typical value of $1000 W/m^2$
- Reference cell temperature for performance rating, T_o a typical value of 25°C with a tolerance of ±2 °C.
- AM =1.5 (A specified light spectral distribution with an air mass). It provide a relative measure of the path of sun must travel through the atmosphere.

In addition to supplying performance parameters at the Standard Test Conditions manufacturers also provide performance data under the Nominal Operating Cell Temperature (NOCT).This is defined as the temperature reached by the open circuited cells in a module under the following conditions:

- Irradiance on cell surface is $800W / m^2$
- The ambient temperature is 20°C (293 K)

To account for other ambient conditions the approximate expression below may be used:

$$T_{cell} = T_{amb} + (N_{oct} - 20)* S / 0.8 \quad (1)$$

Where

T_{cell} is cell temperature (°C);
T_{amb} is the ambient temperature;
N_{oct} is the Nominal Operating Cell Temp &
S is the solar irradiance (kW/m^2).

## III. PHOTOVOLTAIC CONSTRUCTION AND WORKING

In most of solar cells, the absorption of photons takes place in semiconductor materials, resulting in the generation of the charge carriers and the subsequent separation of the photo-generated charge carries. Therefore, semiconductor layers are the most important parts of a solar cell.

A. Silicon Solar Cell

A solar cell is a device that converts the energy of sunlight directly into electricity by the photovoltaic effect [3]. Although there are many kinds of solar cells developed by using different semiconductor materials, the operating principle is identical. The most commonly known solar cell is configured as a large-area p-n junction made from silicon. When a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, a diffusion of electrons occurs from the region of high electron concentration (the n-type side) into the region of low electron concentration (p-type side). Similarly, holes flow in the opposite direction by diffusion [3].
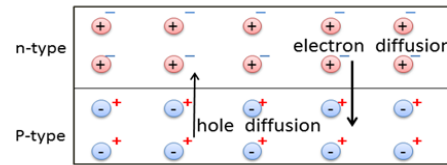
(a) Diffusion current I_D from the p side to the n side
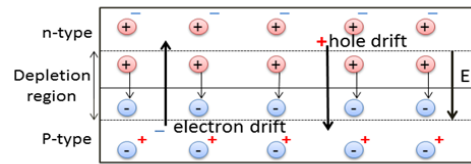
(b) Drift current I_S from n side to the p side and the depletion zone

Fig. 1 I_D, I_S, and depletion zone of a p-n junction

This forms a diffusion current I_D from the p side to the n side Fig. 1 (a). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. The diffusion of carriers does not happen indefinitely because of an electric field which is created by the imbalance of charge immediately on either side of the junction which this diffusion creates. The electric field established across the p-n junction generates a diode that promotes charge flow, known as drift current I_S, that opposes and eventually balances out the diffusion current I_D. The region where electrons and holes have diffused across the junction is called the depletion zone Fig. 1 (b).

B. Photo-generated Current and Voltage

When a visible light photon with energy above the band-gap energy strikes a solar cell and is absorbed by the solar cell, it excites an electron from the valence band. With this newfound energy transferred from the photon, the electron

escapes from its normal position associated with its atom, leaving a localized "hole" behind [3]. When those mobile charge carriers reach the vicinity of the depletion zone, the electric field sweeps the holes into the p-side and pushes the electrons into the n-side, creating a photo-generated drift current. Thus, the p-side accumulates holes and the n-side accumulates electrons Fig. 2 which creates a voltage that can be used to deliver the photo-generated current to a load. At the same time, the voltage built up through the photovoltaic effect shrinks the size of the depletion region of the p-n junction diode resulting in an increased diffusion current through the depletion zone.
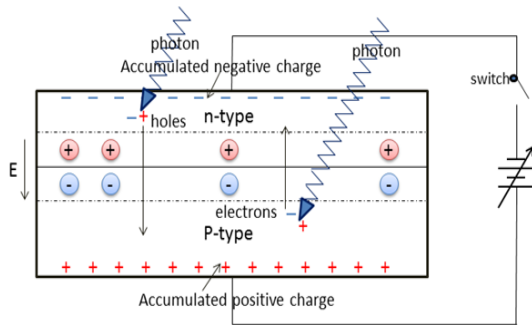

Fig. 2 Illustration of drift current as well as photo-generated current and voltage

Hence, if the solar cell is not connected to an external circuit (switch in the open position in Fig. 2), the rise of the photo-generated voltage eventually causes the diffusion current ID balancing out the drift current IS until a new equilibrium state is reached inside a solar cell [3].

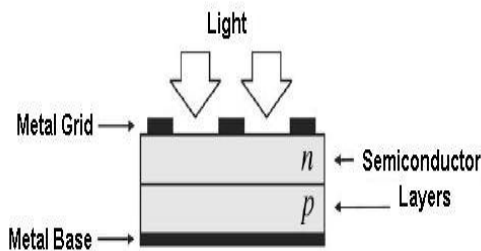### C. P V Cell Constructions

Fig. 3 Photovoltaic Cell Constructions

A photovoltaic cell is basically a semiconductor diode whose p-n junction is exposed to light [1]. Photovoltaic cells is made of several types of semiconductors using different Manufacturing processes. The mono-crystalline and polycrystalline silicon cells are the only found at commercial scale at present era.

Silicon PV cells are composed of a thin layer of bulk Si or a thin Si film connected to electric terminals. One of the sides of the Si layer is doped to form the P–n junction. A thin metallic grid is placed on the Sun-facing surface of the semiconductor. Fig. 3 illustrates the physical structure of PV cell [1], [2].

D. P V Cell Working

Photons of light with energy higher than the band-gap energy of PV material can make electrons in the material break free from atoms that hold them and create hole- electron pairs, as shown in Fig. 2.
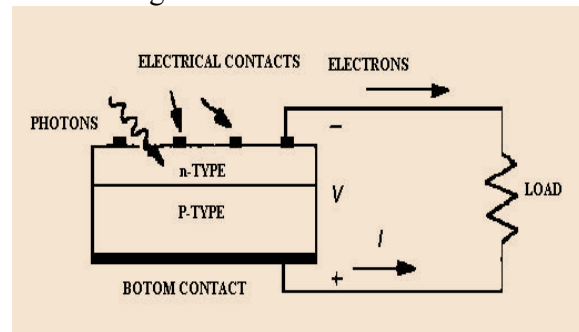

Fig. 4 Working Principle of PV Cell

These electrons, however, will soon fall back into holes causing charge carriers to disappear. If a nearby electric field is provided, those in the conduction band can be continuously swept away from holes toward a metallic contact where they will emerge as an electric current. The PV cell has electrical contacts on its top and bottom to capture the electrons, as shown in Fig. 4. When the PV cell delivers power to the load, the electrons flow out of the n- side into the connecting wire, through the load, and back to the p-side where they recombine with holes [1]. Note that conventional current flows in the opposite direction from electrons [15].

IV. PHOTOVOLTAIC PERFORMANCE

A. Photovoltaic Characteristics

Three classic parameters that are very important on the PV characteristics are:

1. **Short circuit point**, the voltage over the module is zero and the current is at its maximum (short circuit current I_{sc}).

2. **Maximum power point (MPP)**, where the product of current and voltage has its maximum (defined by I_{mpp} V_{mpp}).

3. **Open circuit point**, where the current is zero and the voltage has its maximum (open circuit voltage V_{oc}).

The power delivered by a PV cell attains a maximum value at the points (I_{mp}, V_{mp}). The classical points are shown in Fig. 5 and are usually given as part of a manufacturer's data sheet for a PV module.

Another important parameter of the PV characteristics is called the **Fill Factor (FF)** Fig. 6. It is a term that describes how the curve fills the rectangle that is defined by (V_{oc}) and (I_{sc}). It gives an indication of the quality of a cell's semiconductor junction and measures of how well a solar cell is able to collect the carriers generated by light. It is defined as: [4]
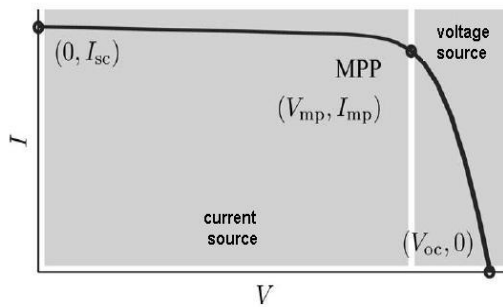

Fig. 5 IV Characteristics of PV

$$FF = V_{mpp}I_{mpp} / V_{oc}I_{oc} \qquad (2)$$

After a simple manipulation the following equation is attained.

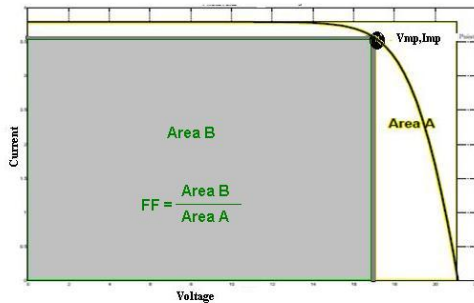$$V_{oc}I_{oc} \, FF = V_{mpp}I_{mpp} = P_{max} \qquad (3)$$

Fig. 6 Photovoltaic module characteristics showing the Fill factor

It can be easily observed that FF is always < 1 and ranges from material to material. The closer the value of the Fill Factor is to unity, the better the operation of the PV cell. *For high quality cells, Fill Factors over 0.85 can be achieved. For typical commercial devices the value lies around 0.68.*

B. Effect of Change in irradiation on I-V Characteristics of the PV Array

In Fig. 7 when the irradiation increases, the current increases more than the voltage and the power at maximum power point P_{mpp} increases as well.
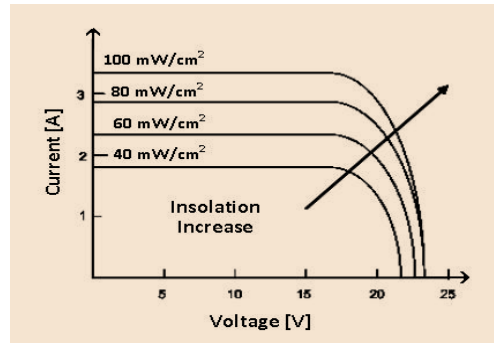

Fig. 7 I-V Characteristics of the PV as functions of irradiation

C. Effect of Change in Temperature on I-V Characteristics of the PV Array

Fig. 8 shows the variation of the current with the temperature, the current changes less than the voltage. Thus, a dynamic point exists on the I-V curve at MPP. The entire PV system has to execute at its maximum output power as shown in Fig. 9 [13]. *The location of the power point maximal is unknown, for that reason we use calculation models and search algorithms methods to sustain the PV array functioning spot at the MPP.*
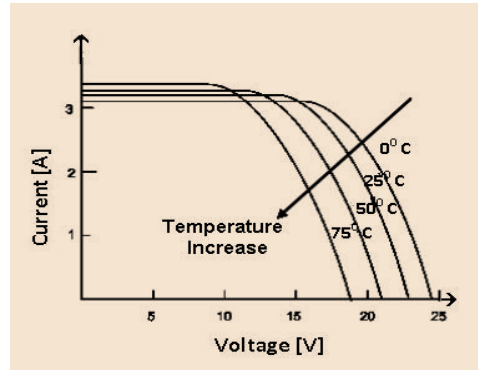

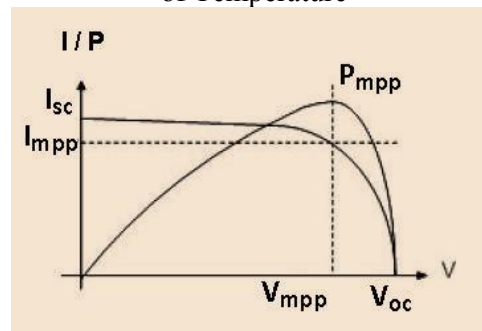Fig. 8 I-V Characteristics of the PV as function of Temperature

Fig. 9 I-V Curves, P-V Curve with the MPP

V. PV CELL MODEL

PV cell is a semiconductor p-n intersection that transforms sunlight to electrical power. To model a solar cell, it is imperative that we assess the effect of different factors on the solar panels and to consider the characteristics given by the manufacturers in the datasheet. It is to be noted that to form a PV module, a set of cells are connected in series or in parallel. Thus, the mathematical models for PV array are attained while utilizing the basic description equivalent circuit of the PV cells [4], [9].

A PV cell is usually embodied by an electrical equivalent of one-diode; series resistance (R_s) and parallel resistance (R_p) is shown in Fig. 10. The different parameters characteristics of the PV cells are:

I_{ph} : currents generated by the solar cells (A)
R_s : resistance in series (Ω)
R_p : resistance in parallel (Ω)
G_a : irradiance from the sunlight (W/m^2)
T_c : cell temperature (K)
I_d : diode current (A)
I : output current of the PV (A)
V : output voltage of the PV (V)

Manufacturer of the solar module gives other parameters needed to model the solar cells. The datasheet which gives the electrical characteristics is calculated under standard test condition STC when the temperature T is 25°C and the irradiance G is 1000 W/m^2.
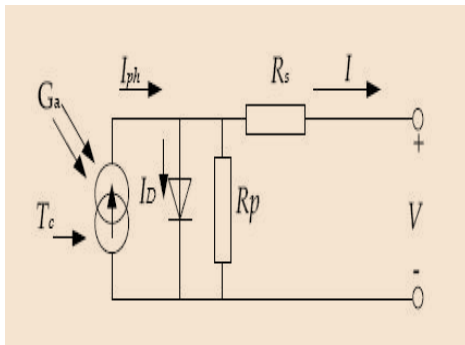

Fig. 10 Equivalent circuit of solar cell with one diode

The parameters that can be found inside the datasheet are

V_{oc} : open circuit voltage (V)
I_{sc} : short-circuit current (A)
P_{mp} : power at maximum power point
V_{mp} : voltage at maximum power point

I_{mp} : current at maximum power point

The solar cell is model first, then extends the model to a PV module, and finally models the PV array. From fig. 10, the output current of the PV cell is [11], [15].

$$I = I_{ph} - I_d \qquad (4)$$

Where

I_{ph} : photon produced by the cell
I_d : diode current

By Shockley equation, the diode current Id is given by

$$I_d = I_0\left(e^{qV_d/kT} - 1\right) \qquad (5)$$

Where

I_o : reverse saturation current of diode
q : elementary electron charge (1.602x10^{-19}C)
V_d : diode voltage
k : Boltzmann constant 1.381x10^{-23} (J/K)
T : temperature in Kelvin (K)

The relation between voltage and current result by replacing the diode current

$$I = I_{ph} - I_d \qquad (6)$$

Current equal to zero calculating at temperature T_1. [4] Where V_d is the output voltage of the PV cell. The reverse saturation I_o is found by using the above equation. By setting the current

$$I_0(T_1) = \frac{I_{ph}(T_1)}{\left(e^{qV_{oc}/kT} - 1\right)} \qquad (7)$$

The current generated by the solar cells I_{ph} can be approximated with the short circuit current I_{sc} in [4]. The current generated can be calculated for other irradiance. The standard current, temperature and irradiance from the datasheet are used to determine the current at different condition [11].

$$I_{sc} \approx I_{ph} \qquad (8)$$

$$I_{sc}(T_1) = \left(\frac{G}{G_{nom}}\right) I_{sc}(T_{1,nom}) \qquad (9)$$

Where

$I_{sc}(T_1)$: current at temperature T_1
$T_{1\ nom}$: the temp. of cell from datasheet at STC
G_{nom} : irradiance from datasheet at STC

After calculation [5], gives the equation of the PV

$$I = I_{ph} - I_0 \left[e^{q\left(\frac{V+I.R_s}{akT}\right)} \right] - \left(\frac{V + I.R_s}{R_p} \right) \qquad (10)$$

Where a, is the diode quality factor between 0 and 1 and must be estimated. The value of "a" is equal to 1 for ideal diode. V is the cell voltage. For a PV module, the cell voltage is multiplied by the total amount of the cells found within the series. The reverse saturation current I_0 depends on the temperature T. It is calculated by the following equation [1].

$$I_0 = I_0(T_1)\left(\frac{T}{T_1}\right)^{\frac{3}{n}} . e^{\frac{qV_q(T_1)}{ak\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \qquad (11)$$

The value of resistance in series R_s is quantified from the slope dv/di of the I- V curve at the point open circuit voltage [7]. The equation R_s is given by

$$R_s = -\frac{dV}{dI} - \frac{akT/q}{I_0 . e^{\left(\frac{qV_{oc}}{akT}\right)}} \qquad (12)$$

The model is completed by using the following recursive equations to find the currents [4]. The recursive equation is used to calculate the current for a PV cell. It is more convenient to solve numerically. The equation introduces a simplified method to calculate resistance in series and neglect the resistance in parallel [15].

$$I_{n+1} = I_n - \frac{I_{ph} - I_n - I_0\left[e^{q\left(\frac{V+I_n.R_s}{akT}\right)} - 1\right]}{-1 - I_0\left(\frac{q.R_s}{akT}\right)e^{q\left(\frac{V+I_n.R_s}{akT}\right)}} \qquad (13)$$

VI. MODEL OF PV MODULE

The following model uses different method to calculate the resistance series and resistance parallel. For example, the BP 3170 is made of 72 solar cells (silicon nitride multi-crystalline) in series and provides 170W of nominal maximum power. The maximum power point's voltage is 35.8V and current delivered at maximum power point is 4.75 A. The parameters of the BP 3170 are given in Table - 1, which is essential to model the PV array.

TABLE I PV MODULE BP 3170 DATASHEET AT STC

Short circuit current I_{sc}	5.2A
Open circuit voltage V_{oc}	44.2
Current at maximum power point I_{MPP}	4.75
Voltage at maximum power point V_{MPP}	35.8
Number of cells in series N_s	72
Temperature coefficient of I_{sc}	(0.065±0.015)%/°c
Temperature coefficient of V_{oc}	- (160±20)mV/°c

Different models of the photovoltaic are developed in so many literatures. The following equation developed in [6] will be used mainly in this report. The model consists of finding the curve characteristic of the PV module from the datasheet.

The goal is to find the values of R_s and R_p that makes the mathematical P-V curve coincide with the experimental peak power at the (V_{mp}, I_{mp}) point. The value of R_s and R_p are reached when the iteration stopped for P_{max} calculated is equal to P_{max} estimated.

The circuit model of the PV module is shown in Fig. 11. It is a controlled current source with the equivalent resistors and the equation of the model above. The variation of the power being taken by the load varies the PV voltage.
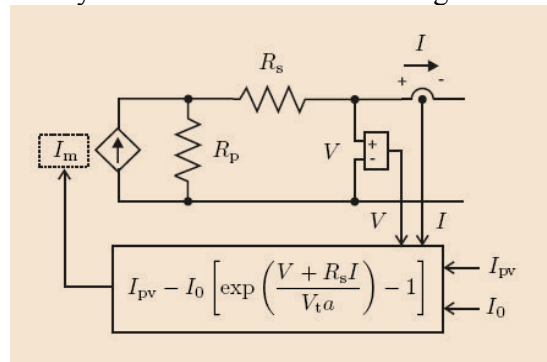

Fig. 11 Circuit model of the photovoltaic module

VII. PHOTOVOLTAIC ARRAY

The PV array is composed of several interconnected photovoltaic modules. The modelling process is the same as the PV module from the PV cells. The same parameters from the datasheet are used. To obtain the required power, voltage and current, the PV modules are associated in series and parallel [14]. The

number of modules connected in series and connected in parallel must be calculated. Fig. 12 shows a photovoltaic array, which consists of multiple modules, linked in parallel and series. N_{ser} is the total quantity of modules within the series and N_{par} is amount of modules in parallel. The number of modules modifies the value of resistance in parallel and resistance in series. The value of equivalent resistance in series and resistance in parallel of the PV array are: [1], [2], [14].

$$R_{s,array} = \frac{R_{s,module} \cdot N_{ser}}{N_{par}}$$

$$R_{p,array} = \frac{R_{p,module} \cdot N_{ser}}{N_{par}} \tag{14}$$

After extending the relation current voltage of the PV modules to a PV array, the new relation of current voltage of the PV array is calculated in [6] by

$$I = I_{pv}N_{par} - I_0 N_{par}\left[\exp\left(\frac{V + R_s\left(\frac{N_{ser}}{N_{par}}\right)I}{V_t a N_{ser}}\right) - 1\right] - \frac{V + R_s\left(\frac{N_{ser}}{N_{par}}\right)I}{R_p\left(\frac{N_{ser}}{N_{par}}\right)} \tag{15}$$

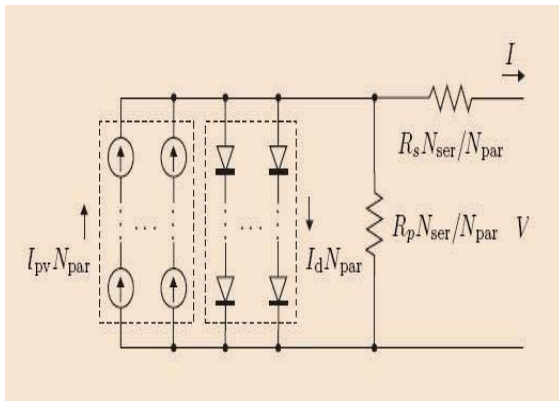Where I_o, I_{pv}, V_t are the same parameters used for a PV modules.

Fig. 12. PV Array composed of N_{ser} x N_{par} modules

This equation is valid for any given array formed with identical modules. The photovoltaic array will be simulated with this equation. The simulation circuit must include the number modules series and parallel. Fig. 13 shows the circuit model of the PV array [15].
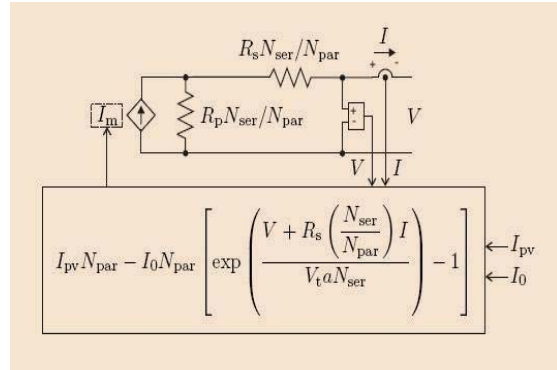

Fig. 13 Model structure of the Photovoltaic array

It constitute from the single- diode photovoltaic I-V model which provides the all necessary information to effortlessly develop a single-diode photovoltaic array model for analyzing and simulating a photovoltaic array.

VIII. SIMULATION OF PHOTOVOLTAIC ARRAY

The simulation of the photovoltaic array is realized with Simulink block. The MATLAB model of the photovoltaic array is based from [2], [16]. The input parameters required for the models are:

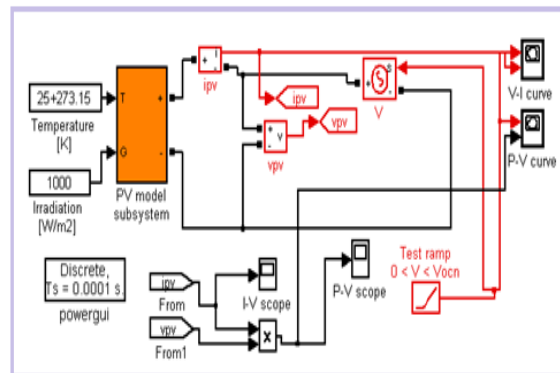|		
N_s	:	number of cells in series
N_{pp}	:	number modules in parallel
N_{ss}	:	number of modules in series
A	:	1.3977, diode constant
K	:	1.38e^{-23}, Boltzmann constant
I_{scn}	:	nominal short-circuit voltage
K_p	:	voltage temperature constant
K_i	:	current temperature coefficient
V_{mp}	:	voltage at maximum power
I_{mp}	:	current at maximum power

Fig. 14 Simulink diagram for the model of the photovoltaic array
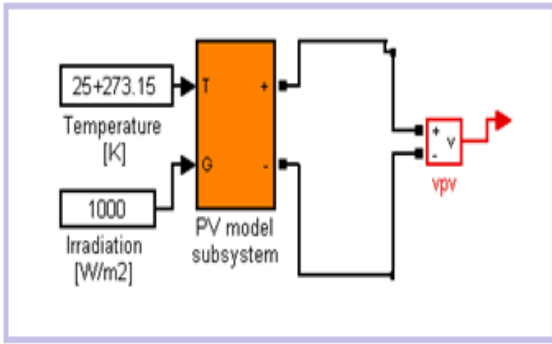
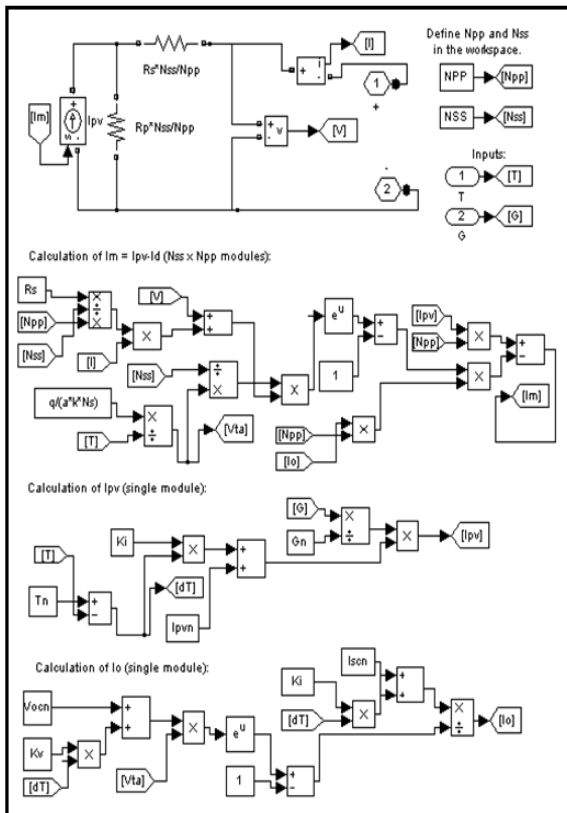Fig. 15 Simulink block of the photovoltaic array / module

Fig. 16 Simulink subsystem model of the photovoltaic array / module

The model of the photovoltaic array has been implemented in Simulink as shown in Fig. 14. The temperature and the irradiance are specified. This simulation allows having the curve I-V and P-V characteristics. The Simulink model uses a current source, voltage source and the value of the resistance in series and parallel of the PV. The number of modules in series and parallel are set with N_{ss} and N_{pp}. The I_m result is used for the Simulink block as a current source to obtain the voltage and current delivered from PV [8], [16].

Fig. 15 is the representation block of the PV that can be used with different power circuits in Simulink. It can be noted that the inputs of the

PV are the irradiation & temperature, the outputs are the voltage and the current. Fig. 16 shows the mask interface of this PV model. The input parameter for this model is the photovoltaic current. The variation of the current from the photovoltaic, varies the photovoltaic output voltage. The Simulink model is derived from the model described in [2], [16].

IX. PHOTOVOLTAIC ARRAY CHARACTERISTICS

In this simulation I-V and P-V characteristics of the PV are simulated only for one module. It means here value of N_{SS} and N_{PP} are taken 1. Fig 17 displays the Simulation results. In Fig. 17(a), the current-voltage characteristics of the PV module BP 3170 is exposed. It can be noted that the maximum current output is 4.75A and the maximum voltage is 35.8 V. These are the same value as given from the manufacturer in Table 1. Fig. 17(b) is the power versus voltage curve. It can be noted that the maximum power of the single module is 170 W [8], [12].
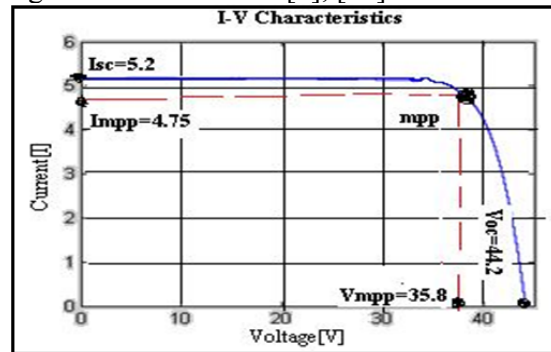

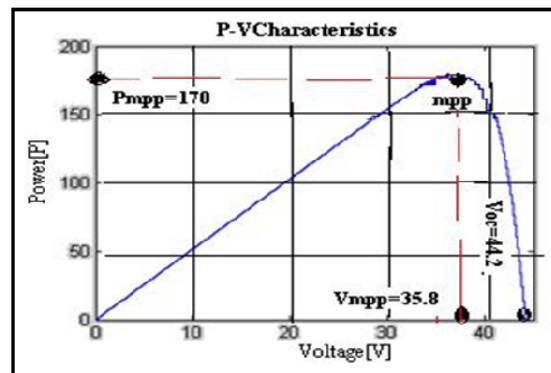Fig. 17 (a) I-V curve of the BP 3170 module at T=25°C and G=1000 W/m^2

Fig. 17 (b) P-V curve of the BP 3170 module at T=25°C and G=1000 W/m^2

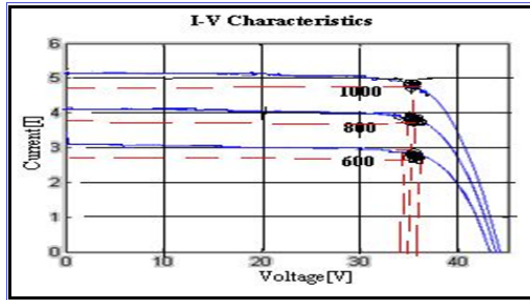## X. SIMULATION OF PHOTOVOLTAIC WITH VARIATION IN IRRADIATION

Fig. 18 (a) I-V curve of the BP 3170 module with variation in irradiation

In this case, the irradiance varies from 600, 800 and 1000 and the temperature is constant. The Simulink model in Figure 14 was used. The result in The Fig. 18 (a) is the current- voltage curve, which shows the current decreases significantly when the irradiance decreases [6].
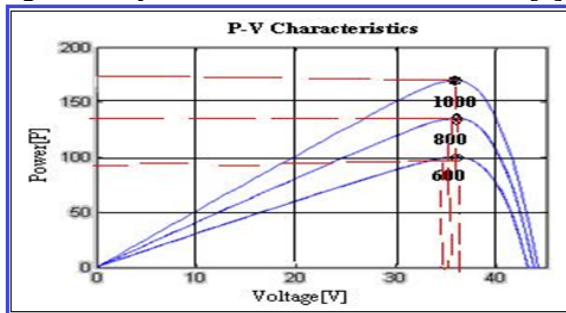

Fig. 18 (b) P-V curve of the BP 3170 module with variation in irradiation

Fig. 18 (b) is the power-voltage curve which shows that the maximum power of the PV decrease when the irradiance decreases.

XI. CONCLUSION

PV array constitutes from Single- diode PV model provides the all necessary information to develop effortlessly a single - diode photovoltaic array model for analysis and simulation [Fig.13].

From the simulation result maximum output current is 4.75A & the maximum voltage is 35.8 V. These are the same value as specified in the datasheet of manufacturer (Table 1). Simulation result [Fig. 17(b)] maximum power delivered by the single module is 170 W is again matches with datasheet.

We observed that the current & the maximum power of the PV decrease significantly, when the irradiance decreases at secured temperature [Fig 18(a) & (b)].

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