Modelling of Photovoltaic Cell/Module under Environmental Disturbances using MATLAB /Simulink

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Abstract- **Integration of photovoltaic power to grid is one of the major interests. Design, study and analysis of key components in a photovoltaic power system from generation of power to integration to main grid are very crucial. It is important to build an accurate photovoltaic module and analyse characteristics of the PV (photovoltaic) cell/module under different environmental parameters. Further, for the design of an efficient MPPT algorithm the range of maximum power to be tracked is necessary. This paper presents a step by step mathematical model for a PV cell/module based on single diode equivalent circuit model. And compared the simulated model results with manufacturer's specified specifications like peak current, peak voltage, open circuit voltage and short circuit current under variation of irradiation, temperature. Model evaluation is presented using a WEBEL SOLAR W2300 250W Monocrystalline module in MATLAB /SIMULINK platform. The simulated result shows the performance matching of the cell/module.**
Keywords: grid interconnection, irradiation, MATLAB/Simulink, PV module, temperature

Nomenclature Used:

I_{cell} – output current of a cell
I_m – output current of a module
I_{sc}– Short circuit current of the cell at reference temperature
I_{sh} –current through shunt resistor branch.
I_s –reverse saturation current at reference temperature
I_{mp}–current at Maximum power condition
V – terminal   voltage of the cell/module
V_{oc} – open circuit voltage at reference temperature.
V_{mp}– voltage at Maximum power condition
V_t – thermal voltage of cell/module at reference temperature
R_{sh} – shunt resistance
R_s – series resistance
K –Boltzmann's constant $=1.3806503 \times 10^{-23}$ J/k
q – electron charge $1.60217646 \times 10^{-19}$ C
N– diode ideality constant
I_r– irradiation in W/m^2
P–output power of the cell/module
η – efficiency of the cell/module.
P_m –maximum power
A_c = area of the cell/module (m^2).
E – input light energy (W/m^2) or Ambient Irradiation

K_i– short circuit current co-efficient in A/^{0}C
T_{ref} – reference temperature in Kelvin
T – temperature of cell/module in Kelvin
E_g– band gap energy in electron volt

I. INTRODUCTION

Increase in demand of electricity   and depletion of fossil fuel leads to think of alternate energy resources. Lots of promising results are shown especially with solar energy. And it is helping to overcome the dearth of electricity in present and   near future. In recent year's photovoltaic power system have drawn considerable research attention where in modelling and computer simulations are necessary to analyse the system operation and integration with utility grids.

A Photovoltaic system is one of the most able technologies because of its long life, clean, environmental friendly and reliable nature [1]. Photovoltaic (PV) generation has increased by 20% to 25% over the past two decades. The demand for PV systems is growing worldwide. Research activities are being conducted in this direction for improvement in their efficiency, cost and reliability for better utilization [2].

Integration of   solar energy to modern electric grid is increasing with wide acceptance of photovoltaic power systems. PV module to operate at highest energy conversion one needs to know the maximum power point. The output voltage, current and power of cell/module varies as function of irradiation and temperature. Hence it is essential to study and understand the effect of these parameters in PV system design .Also it is essential to model it for the analysis of photovoltaic power systems under the influence of these parameters.

II. WORKING OF A PHOTOVOLTAIC CELL

Solar cell is a junction of p-n layer fabricated with thin wafer of *p-n* semiconductor material. The solar cell converts the electromagnetic radiation of solar energy directly in to electricity by photovoltaic effect [3]. The basic construction of solar cell is shown in Fig.1. When light containing photons of sufficient energy incident on the cell it generates electrons that originate an electric current if the cell is short-circuited. This phenomenon depends on the semiconductor material and wavelength of the incident light.

The photovoltaic process is described as the absorption of solar radiation, the generation and transport of free carriers at the p–n junction, and the collection of these electric charges at the terminals of the PV device. The rate of generation of electric carriers depends on the flux of incident light and the capacity of absorption of the semiconductor.

The most common semiconductor material used for manufacturing of solar cells is silicon because of its easy fabrication process and   economically feasible for large scale.
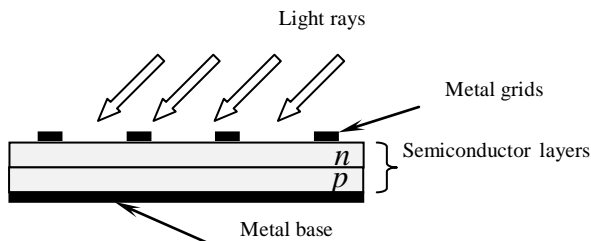
Fig. 1 Photovoltaic cell structure [7]

Other materials can achieve better conversion efficiency, but at higher and commercially unfeasible costs. There are various types of photovoltaic cells like mono-crystalline, poly-crystalline and amorphous silicon, compound thin film etc., Efficiency and life of cell varies based on type of construction and material used. Mono-crystalline silicon   (c-Si) is most expensive compared to other types and popular [4].

A typical PV cell generates an open circuit voltage around 0.5 to 0.7 volts depending on the semiconductor and the built-up technology. Therefore the cells must be connected in series configuration to form a PV   module to increase the voltage. Further, modules are connected in series and parallel configuration to form a PV array, which in turn increases the total power of the system [5]. A typical arrangement of   cells in series, a module and modules in series and parallel to form an array is shown in Fig. 2 (a), (b) and (c).
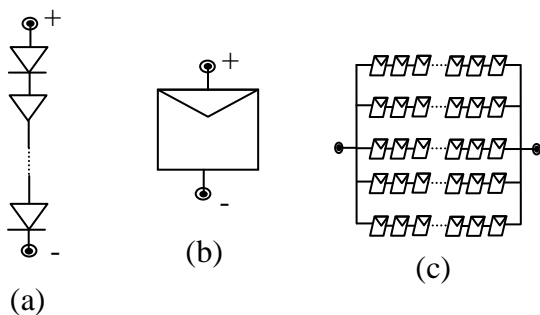

Fig. 2 Photovoltaic (a) cell (b) Module and (c) Array

III. MATHEMATICAL MODEL OF PHOTOVOLTAIC CELL/MODULE

A photovoltaic cell/module is   mathematically modelled using single diode equivalent circuit. The various parameters which influence the characteristic of a cell are classified as environmental parameter like irradiance and temperature, internal parameter like ideality constant, Boltzmann constant energy band-gap and charge of electron, electrical parameter like open circuit voltage, short circuit current, series resistance, and shunt resistance.

A mathematical model of single diode PV cell is developed based on current-voltage relationship of a solar cell. An ideal PV cell is represented by a current source and an anti parallel diode connected to it. A practical PV cell is an addition of equivalent series and a shunt resistance parameter to an ideal PV cell. Fig.3. shows the ideal and practical PV cell of single diode model [7].
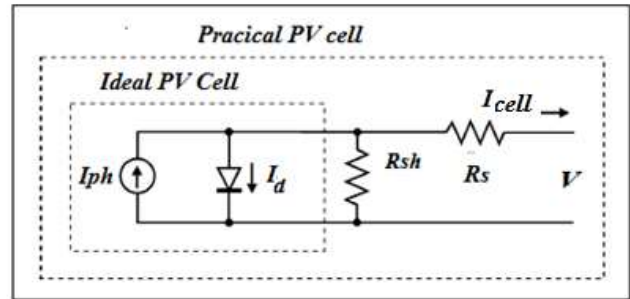

Fig.3 Equivalent circuit of Photovoltaic cell [7]

According to [5] Kirchhoff's current law, output current of an ideal cell is   given by,

$$I_{cell} = I_{ph} - I_d \tag{1}$$

The net cell output current (I_{cell}) is difference of the light-generated current (I_{ph}) and the diode current (I_d) which is expressed by Shockley diode equation

$$I_d = I_s \left(e^{\frac{qV}{NKT}} - 1 \right) \tag{2}$$

For practical PV cell,

$$I_{cell} = I_{ph} - I_d - I_{sh} \tag{3}$$

$$I_{cell} = I_{ph} - \left[I_s \left(e^{\frac{qV}{NKT}} - 1 \right) \right] - \frac{(V + IR_s)}{R_{sh}} \tag{4}$$

$$I_{sh} = \frac{(V + I_{cell}R_s)}{R_{sh}} \tag{5}$$

$$I_{ph} = I_r \times \frac{I_{sc}}{1000} \tag{6}$$

The ideality constant is responsible for the various mechanisms for moving carriers across the junction. The parameter *N* is equal to 1 if the mobility process is purely diffusion and *N* is equal to 2 if it is primarily recombination in the depletion region. In this work *N* is taken as 1.2   and assumed to be related only to the material of the solar cell and independent of solar irradiation [6].

A series resistance R_s is more dominant when the device operates in the voltage source region and depends on the contact resistance of the metal base with the *p* semiconductor layer, the resistance of the *p-n* bodies, the contact resistance of the *n*-layer with the top metal grid and the resistance of the metal grid. Shunt resistance representing the reverse leakage current of the diode. R_{sh} has stronger influence on the current source region of operation [7]. To find value of reverse saturation current I_s, considering open circuit condition I_{cell} =0, and at short circuit condition I_{cell} =I_{sc} hence short circuit current I_{sc} is equal to the light generated current I_{ph} and is given by

$$I_s = \frac{I_{sc}}{e^{\frac{V_{oc}}{NKT}} - 1} \qquad (7)$$

Series resistance (R_s) and shunt resistance (R_{sh}) minimum and maximum limits are calculated using (8) and (9) and values are taken well within the limits.

$$R_s < \frac{0.1 * V_{oc}}{I_{sc}} \qquad (8)$$

$$R_{sh} > \frac{10 * V_{oc}}{I_{sc}} \qquad (9)$$

The PV module is typically composed of a number of PV cells in series. The generalized equation for a PV module connecting N_s number of cells in series can be written as

$$I_m = I_{ph} - \left[I_S \left(e^{\frac{(V_m + I_m R_s N_s)}{N_s V_t}} - 1 \right) \right] - \frac{(V_m + I_m R_s N_s)}{N_s R_{sh}} \qquad (10)$$

$$V_t = \frac{NKT}{q} \qquad (11)$$

$$P = V * I \qquad (12)$$

Efficiency is the ratio between the maximum power and the incident light power. The efficiency of the module is given by

$$\eta = \frac{P_m}{E A_c} \qquad (13)$$

Fill factor is the ratio of the maximum power that can be delivered to the load and the product of I_{sc} and V_{oc}

$$Fill\ Factor\ (FF) = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \qquad (14)$$

The fill factor is a measure of the real *I-V* characteristics [5].

IV. MATLAB/SIMULINK Model

The mathematical model of cell, module are implemented in MATLAB/SIMULINK R2012b.It is difficult to arrive an analytical solution for a set of model parameter because of implicit and nonlinear nature of equations. Hence the manufacturer's specification is used to evaluate the behavioural characteristics I-V and P-V. Data sheet gives the following operational data on PV modules: the open-circuit voltage (V_{OC}), the short-circuit current (I_{SC}), current at maximum power (I_{MP}), voltage at maximum power (V_{MP}), and the temperature coefficients of open-circuit voltage (a_T) and short-circuit current (K_I), maximum power (P_T).The mentioned data are at standard test conditions (STC) which is at solar irradiation of 1000 W/m^2 and temperature (T) 25^{0}c and air mass of 1.5.The term STC represents the standard test conditions used to measure the nominal output power of photovoltaic cell/module [8].

A step by step procedure to model photovoltaic cell, module and its behaviour during temperature and irradiation variation are presented. It is carried out in 10 different steps. Initially a single photovoltaic cell is modelled using (1) to (9)

at STC [1] and extended to develop a module considering 60 numbers of cells in series to obtain 250W using (10) at STC. Further the same module is modelled to evaluate the effect of temperature and irradiation using (15) and (16).

Step 1: Physical parameters are defined using "Goto" function block like *K, q, N, Eg* which remains constant throughout the simulation and is as shown in Fig.4.
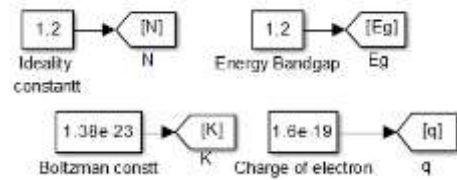

Fig. 4 Physical parameter constant block

Step 2: Operating temperature (T) and desired irradiance (I_r), temperature coefficient of short circuit current (K_i) is defined using "Goto" block and is as shown in Fig.5.
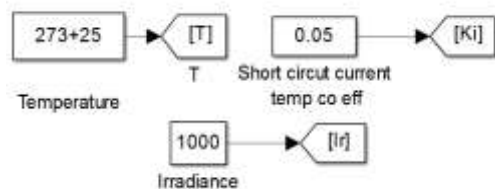

Fig. 5 Environmental parameter constant block

Step 3: Series and shunt resistance (R_s and R_{sh}) is calculated using (8) & (9), and considered suitably within the limits. Further, the value of V_{oc} and I_{sc} are defined from the data sheet, number of series cell (N_s) is also defined as shown in Fig.6.
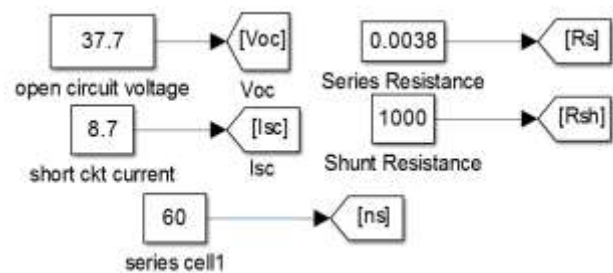

Fig. 6 Electrical parameter constant block

Step 4: V_t (thermal voltage) is modelled with the parameters defined in *step 1* using (11) at reference temperature as shown in Fig.7.
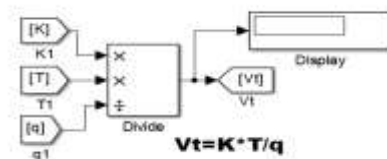

Fig. 7 Sub system of thermal voltage (V_t)

Step 5: Reverse saturation current of diode (I_s) is modelled using parameters in *step1* and *step3* using (7) and is as shown in Fig.8.The parameter V_{oc} and I_{sc} are referred from data sheet of a module. For a cell, V_{oc} is calculated using open circuit voltage divided by number of series cells
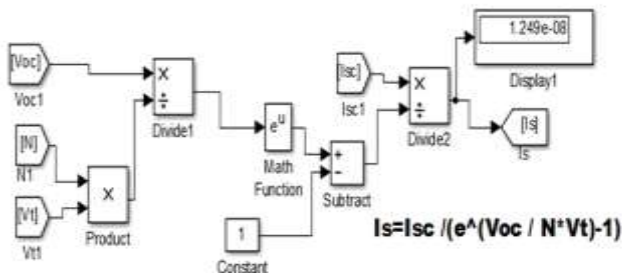

Fig. 8 Subsystem of reverse saturation current at reference Temperature

Step 6: Diode current is calculated by Shockley diode equation given in (2) ,using the parameters defined in step1-step5 and is as shown in Fig.9.
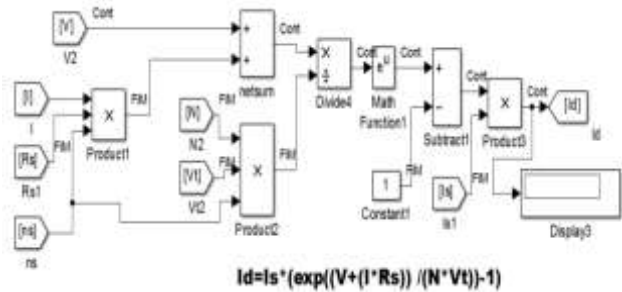

Fig. 9 Subsystem of diode current

Step 7: Shunt current (I_{sh}) , flowing through the shunt resistor is calculated using (5) and is as shown in Fig.10.
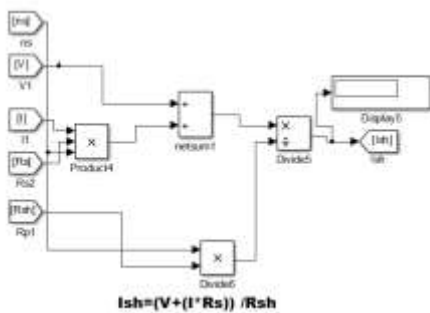

Fig. 10 Subsystem of shunt current

Step 8: Light generated current at desired irradiance (I_{ph}) *is* calculated *by* considering the value of short circuit current *(I_{sc})* defined in *step 3* using (6) and is as shown in Fig.11.
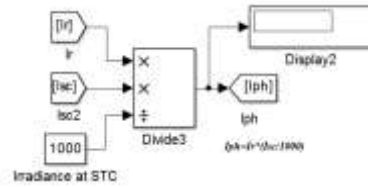

Fig. 11 Subsystem of light generated current (I_{ph})

Step 9: To plot the characteristics, repeating sequence block is considered indicating the voltage levels for output voltage (*V*) and is as shown in Fig.12.
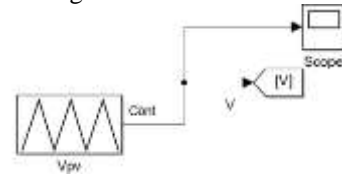

Fig. 12 Repeating sequence block of voltage

Step 10: All the subsystems are combined and using (3) resultant output current *I* of cell/module is calculated by reverse saturation current (I_s) from *step 5* diode current (I_d) from step 6, light generated current (I_{ph}) from *step 8* . And power (*P*) is found from product of output voltage and current (*I*) using (12). An I-V and P-V characteristics are plotted using X-Y graph block and is as shown in Fig.13.
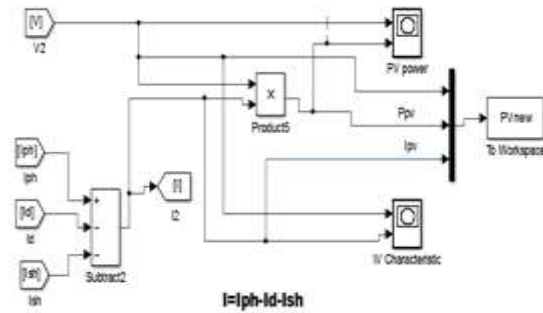

Fig.13 Complete   Model of cell/module

TABLE 1
DATA SHEET OF WEBEL SOLAR W2300 SERIES 250W MODULE AT STC

Parameter	Specification
Type -Mono crystalline	
Module Dimension: 1645 x 992 x 42 mm	
Single Cell Dimension:156 x 156mm	
Power	250*W*
Open circuit Voltage *(V_{oc})*	37.70*V*
Short circuit Current (I_{sc})	8.68*A*
Voltage at maximum Power (V_{mp})	30.5*V*
Current at maximum Power (I_{mp})	8.2*A*
Temp. Co-eff. Power P_m (P_T)	-0.45% / ^{0}K
Temp. Co-eff. Voltage V_{oc} (a_T)	-0.34% / ^{0}K
Temp. Co-eff. Current I_{sc} (K_i)	+0.05% / ^{0}K
Weight	21.0Kg

V. Effect of Irradiation and Temperature on PV module

The amount of radiation that reaches the ground is reasonably variable. In addition to the regular daily and yearly variation due to the apparent motion of the Sun. Irregular variations are caused by the climatic conditions like cloud cover as well as by the general composition of the atmosphere. This variation affects overall performance of the photovoltaic module.

The light generated current I_{ph} depends on the solar irradiation and temperature according to (15).

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})] \times \frac{I_r}{1000} \qquad (15)$$

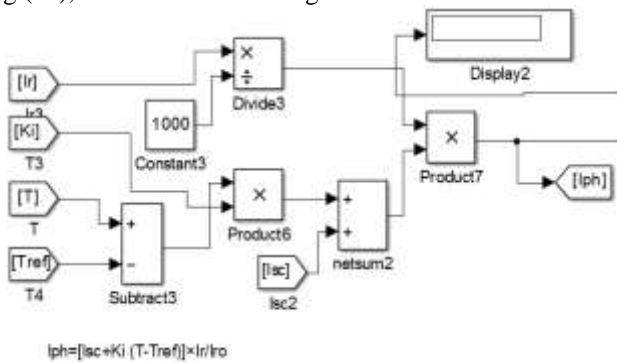Mathematical model for effect of irradiance is modelled using (15), and is as shown in Fig. 14.

Fig. 14 Sub system of light generated (I_{ph}) current at desired irradiation and temperature.

The prominent parameter which is to be calculated during variation of temperature is the diode reverse saturation current .It varies as cubic function of temperature and it is given by (16) and mathematical model of variation in temperature is modelled and is shown in Fig.15.

$$I_s(T) = I_s \left(\frac{T}{T_{ref}}\right)^3 exp \left[\left(\frac{T}{T_{ref}} - 1\right) \frac{E_g}{NV_t} \right] \qquad (16)$$
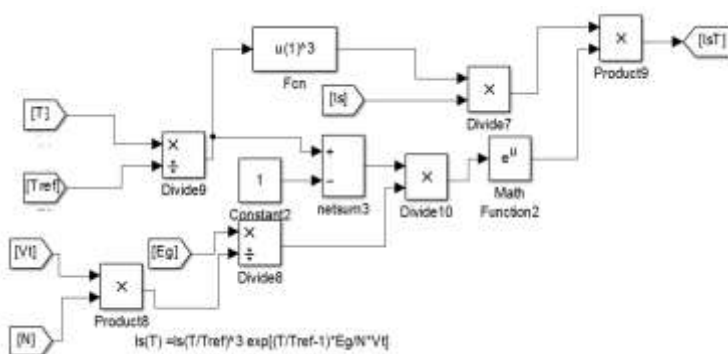
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Fig. 15 Subsystem of reverse saturation current at desired temperature

The current I_{ph} calculated using (15) and model is shown in Fig.14 of irradiation variation, the current I_s is calculated using (16) and model is shown in Fig.15 of temperature variation and resultant output current I ,output power P is found using (3) from step 10.

VI. Results and Discussion

A series of simulations   are conducted using the parameters mentioned in Table 1. Simulations are limited to cell and module level only. A typical module of 250 W which is a part of 2 KW experimental setup and is shown in Fig. 16.

A. Performance of a Single PV cell at STC

The simulated I-V and P-V characterstic of a single cell at STC, is shown in Fig.17 and Fig.18, and are matching with standard chracterstics
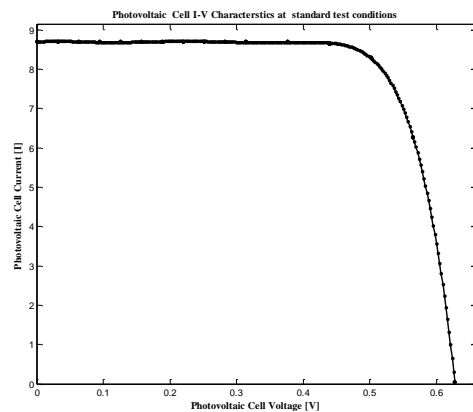

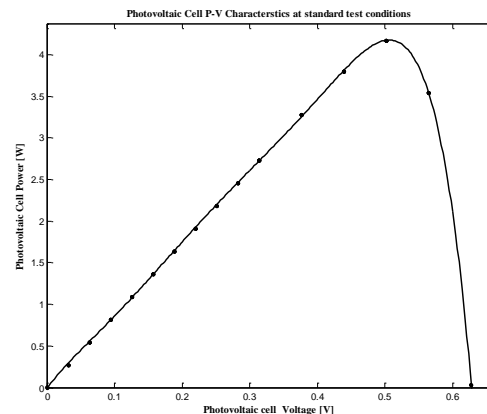Fig. 16 Installed WEBEL 2300 250W Module

Fig.17 I-V Characteristic of a Cell

Fig. 18 P-V Characteristic of a Cell
TABLE 2

SIMULATED RESULTS OF A CELL AND A MODULE

Parameter	Values	
	Cell	**Module**
V_{oc} (V)	0.628	37.7
I_{sc} (A)	8.7	8.7
V_{mp} (V)	0.5175	30.16
I_{mp} (A)	8.01	8.288
P_m (W) From I-V Characteristics (calculated)	4.145	249.9
P_m (W) From P-V characteristics	4.176	250
Fill Factor	0.75	0.76
Efficiency (%)	17.15	15.7

B. Performance of a Module at STC

Simulated I-V and P-V characterstic of a module is shown in Fig.19 and Fig.20. These simulated test results along with its performance parameter like efficiency and fill factor for a cell and module are tabulated in Table 2 and are agreeing with manufacturer's specifcation. The area of cell/module is found from manufacturer data sheet and efficiency , fill factor is caluclated using (13),(14) .
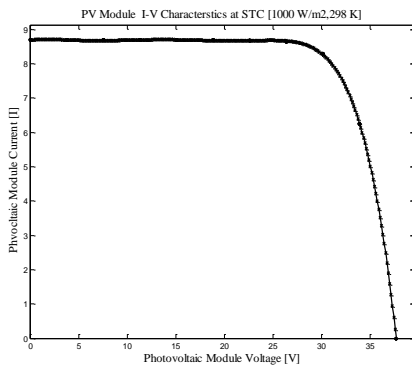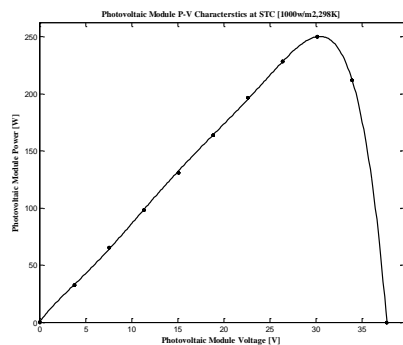

Fig. 19 I-V Characterstic of a Module

Fig. 20 P-V Characterstic of a Module

C. Performance of Module for various irradiation level

The I-V,P-V characteristics of module for various conditions of irradiation at constant temperature (298 K) are shown in Fig. 21and Fig.22 and results are tabulated in Table 3. The efficiency and fill factor is found using (13),(14). It is

found that output current, output power strongly depends on irradiation. However the open circuit voltage has very small increase as the irradiation is varied from 700W/m² to 900W/m².

D. Performance of Module for various temperature level.

The I-V and P-V corresponding characteristics curves for three different tremperature values at constant irradiation of 1000 W/m² is as shown in Fig.23 and Fig.24. The efficiency and fill factor is found using (13),(14). Table 4 shows the data tabulated during these trials. These simulated results indicated a good agreement with the expected characteristics of a module.
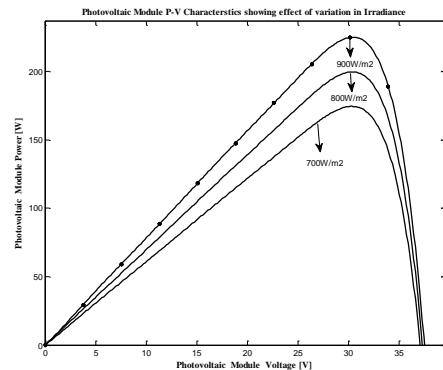

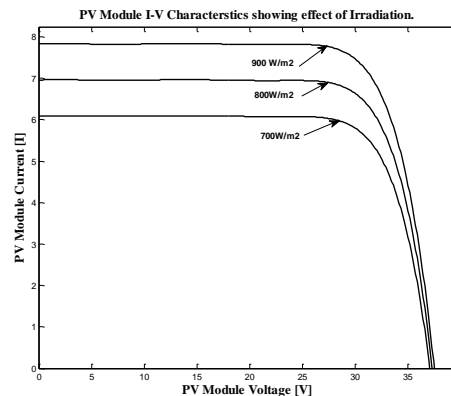Fig .21 Effect of Irradiance on P-V Characteristics of a Module

Fig. 22 Effect of Irradiance on I-V Characteristics of a Module

TABLE 3
SIMULATED RESULTS OF IRRADIATION EFFECT ON 250W MODULE

Trial	1	2	3
Irradiance (W/m²) →	**700**	**800**	**900**
V_{mp} (V)	30.16	30.16	30.16
I_{mp} (A)	5.788	6.625	7.459
P_m (W) From I-V Characteristics (calculated)	174.5	199.81	224.96
P_m (W) From P-V characteristics	174.6	199.8	225
Fill Factor	0.77	0.77	0.76
Efficiency (%)	10.6	12.2	13.74

TABLE 4

SIMULATED RESULTS OF TEMPERATURE EFFECT ON 250 W MODULE

Trial	1	2	3
Temperature (K) →	313	328	343
V_{mp} (V)	26.52	23.68	20.13
I_{mp} (A)	8.297	8.049	7.97
P_m (W) From I-V Characteristics (calculated)	220.03	190.6	160.4
P_m (W) From P-V characteristics	220.3	191.8	160.8
Fill Factor	0.74	0.71	0.67
Efficiency (%)	13.4	11.6	9.79

It is found that for a 250W module, for every 100 W/m² irradiance decrease approximately a 10% reduction in maximum power, 10% reduction in short circuit current is observed. Also found that increase in cell/module temperature decreases the maximum power, open circuit voltage as well as small percentage increase in short circuit current. The deviation in various parameters referred to standard test conditions are shown as percentage change in respective parameters and is tabulated in Table 5 and Table 6.

The performance of the module is poor when increase in temperature and decrease in irradiance and it is clearly indicated by efficiency and fill factor parameter and is shown in Table 3,4.
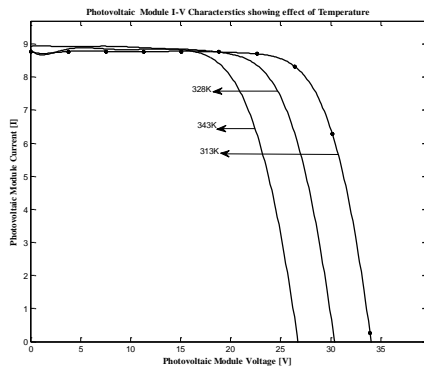

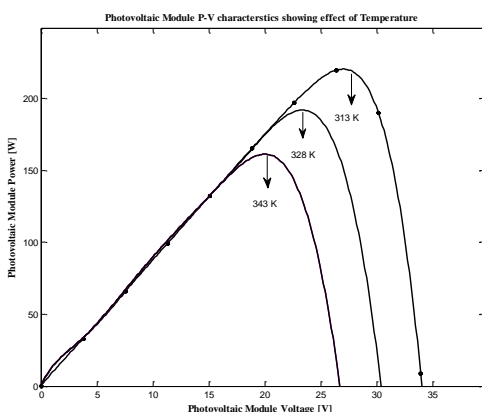Fig. 23 Effect of Temperature on I-V characteristics of a Module

Fig. 24 Effect of Temperature on P-V characteristics of a Module

TABLE 5

EFFECT OF IRRADIANCE ON VARIOUS PARAMETERS OF 250W MODULE

Trial	1	2	3
Irradiance (W/m²) → Deviation (%) ↓	700	800	900
ΔP_m	30.16	20.08	10
ΔV_{mp}	1.11	1.11	1.11
ΔI_{mp}	29.4	19.2	9.07
ΔV_{oc}	2.38	1.5	0.74
ΔIsc	30	20	10

TABLE 6

EFFECT OF TEMPERATURE ON VARIOUS PARAMETERS OF 250W MODULE

Trial	1	2	3
Temperature (K)→ Deviation (%) ↓	313	328	343
ΔP_M	11.88	23.2	35.68
ΔV_{MP}	13.05	22.36	34.0
ΔI_{MP}	-1.18	1.84	2.80
ΔV_{OC}	9.68	19.49	29.28
ΔI_{SC}	-1.09	-1.5	-2.89

VII.   CONCLUSION

A step by step mathematical model of PV cell/Module is developed in Matlab /Simulink environment. The dynamic characteristics like I-V and P-V curves at STC shows excellent correspondence to manufacturers provided curves. Also the performance of the cell/ module during variation in irradiation and temperature is analysed. The result helps in finding the range of maximum power, which leads to accurate design of maximum power point tracker (MPPT). The performance of the cell/module during these conditions helps in designing a most accurate grid connected photovoltaic power system.

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