Modeling and Simulation of Photovoltaic Arrays

Snehamoy Dhar[1], PG Scholar; R Sridhar[2], Asst. Professor (Sr.G) and Varun Avasthy[3], PG Scholar
snehamoydhar@gmail.com, sridharmanly@gmail.com, varun.avasthy@gmail.com
Department of Electrical & Electronics Engineering,
SRM University, Chennai

Abstract: **This paper proposes a method of modeling and simulation of Photovoltaic (PV) arrays. The main objective here is to achieve a circuit based simulation model of a Photovoltaic (PV) cell in order to estimate the electrical behavior of the practical cell with respect to change in environmental parameters like irradiation and temperature. The modeling of PV array serve as a fundamental component for any research activity related with PV system. The proposed method is implemented in MATLAB/Simulink environment and the results reveal that the array output is nonlinear in nature and nearly constant current up to open circuit voltage and the power has maximum pick with respect to the voltage for particular environmental condition.**

***Keywords*— Open-circuit voltage (V_{oc}), Maximum power point (MPP), Photovoltaic (PV) Cell, Stand-alone Photovoltaic (PV) system, Standard Test Condition (STC), Short-circuit current (I_{sc}), voltage and current at the maximum power point (V_{mpp} & I_{mpp}),**

I. INTRODUCTION

RENEWABLE energy resources will be an increasingly important part of power generation in the new millennium. Besides assisting in the reduction of the emission of greenhouse gases, they add the much- needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels. The energy that reaches the earth surface is around 3.2 EJ/y. If we are able to harvest even a small fraction of the available energy at the earth surface we could solve our energy problems. A Photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays [7]. This paper focuses on modeling photovoltaic modules or panels composed of several basic cells. The term array used henceforth means any photovoltaic device composed of several basic cells.

The power produced by a single module is seldom enough for commercial use, so modules are connected to form array to supply the load. The connection of the modules in an array is same as that of cells in a module. Modules can also be connected in series to get an increased voltage or in parallel to get an increased current [2],[4].

The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid connected systems. The purpose of this paper is to present a brief introduction to the behavior and functioning of a PV device and write its basic equations, without the intention of providing an in-depth analysis of the PV phenomenon and the semiconductor physics.

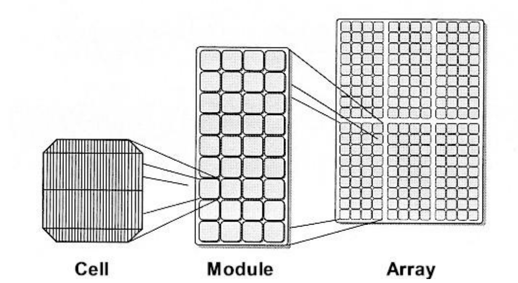

Fig 1: Photovoltaic Hierarchy

The efficiency of a PV device is dependent on the spectral distribution of solar radiation. The evaluation of PV devices is generally done with reference to a standard spectral distribution. Usually we specify standard conditions. This is done so that a comparison on the basis of performance between different PV cells can be done. The parameters are generally given in a datasheet. The datasheets provide remarkable parameters regarding the performance and characteristics of PV arrays with respect to these standard test conditions. The nominal (standard) test conditions are as follows:

$$Irradiance(G_n) = 1000\frac{W}{m^2}$$

$$Temperature(T_n) = 25^0 C$$

$$Solar\ Spectrum\ Density\ distribution = 1.5A.M$$

Therefore it is desirable that the semiconductor used for photo-absorption have band gap energy such that maximum percent of solar spectrum is efficiently absorbed. However, in the current scenario it is possible to arbitrarily classify a select group of materials into different efficiency regimes:
(1) ultrahigh-efficiency devices (η>30%) are typically achieved by using multi junction tandem cells involving semiconductors like GaAs and $GaInP_2$; (2) high-efficiency cells (η>20%) are generally fabricated by using high-quality, single-crystal silicon materials in novel device configurations that take advantage of advances in microelectronic technologies; (3) high-efficiency cells (η=12%-20%) are typical of a number of polycrystalline and amorphous thin-film semiconductor materials such as polycrystalline silicon, amorphous and microcrystalline silicon, copper gallium indium selenide (CIGS), and cadmium telluride (CdTe); and (4) moderate-efficiency cells (η<12%) are typical of some of the newer materials such as dye-sensitized nanostructure TiO2

solar cells, which have the potential for being very low-cost devices.

The aim of this paper is to provide the reader with all necessary information to develop photovoltaic array models and circuits that can be used in the simulation of power converters for photovoltaic applications. For performance comparison between Actual and Mathematical equation stands for solar array It needs to design a equivalent Photovoltaic (PV) model. Simulation is a equivalent circuit model of real life PV panes. The output of model is more ideal then the real one. The whole simulation is done in MATLAB/Simulink environment.

II. How a PV cell works

A photovoltaic cell is basically a semiconductor diode whose *p–n* junction is exposed to light. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The monocrystalline and polycrystalline silicon cells are the only found at commercial scale at the present time. 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. 2 roughly illustrates the physical structure of a PV cell.

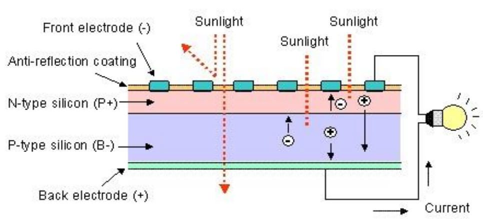

Fig 2: Working of PV cell

Working of a PV cell is based on the basic principle of photoelectric effect. Photoelectric effect can be defined as a phenomenon in which an electron gets ejected from the conduction band as a consequence of the absorption of sunlight of a certain wavelength by the matter (metallic or non-metallic solids, liquids or gases).So, in a photovoltaic cell, when sunlight strikes its surface, some portion of the solar energy is absorbed in the semiconductor material. If absorbed energy is greater than the band gap energy of the semiconductor, the electron from valence band jumps to the conduction band. By this, pairs of hole-electrons are created in the illuminated region of the semiconductor. The electrons thus created in the conduction band are now free to move. These free electrons are forced to move in a particular direction by the action of electric field present in the PV cells. These flowing electrons constitutes current and can be drawn for external use by connecting a metal plate on top and bottom of PV cell. This current and the voltage (created because of its built-in electric fields) produces required power.

III. Characteristics of a PV cell

In a PV characteristic there are basically three important points viz. open circuit voltage, short circuit current and maximum power point. The maximum power that can be extracted from a PV cell are at the maximum power points. Usually manufacturers provide these parameters in their datasheets for a particular PV cell or module. By using these parameters we can build a simple model but for more information is required for designing an accurate model.

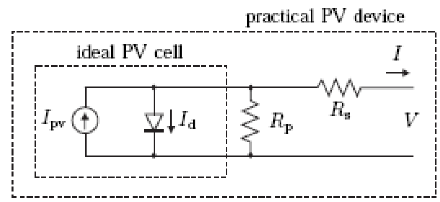

Fig 3: Single-diode model of the theoretical photovoltaic cell and equivalent circuit of a practical photovoltaic device including the series and parallel resistances.

The ideal photovoltaic cell is represented in Fig. 3 as equivalent circuit model. The basic equation from the theoretical operation of semiconductors that mathematically describes the I-V characteristic of the ideal photovoltaic cell is:

$$I = I_{PV,cell} - I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right] \quad (1)$$

Eq. 1: the I-V characteristic of the ideal PV cell

where $I_{pv,cell}$ is the current generated by the irradiation of sun light, Id is the Shockley diode equation, I0,cell is the reverse saturation or leakage current of the diode, q is the charge of an electron [1.60217646x10−19C], k is the Boltzmann constant [1.3806503x10−23J/K], T is the temperature of the *p-n* junction in Kelvin, and a is the diode ideality constant. Fig. 4 shows the I-V curve originated from Eq.(1).

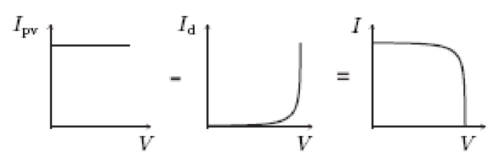

Fig 4: Characteristic I-V curve of the photovoltaic cell. The net cell current I is composed of the light-generated current Ipv and the diode current Id.

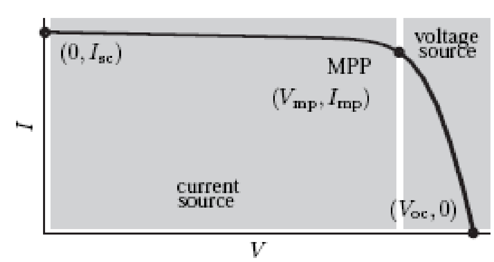

Fig 5: Characteristic I-V curve of a practical photovoltaic Device and the three *remarkable points*: short circuit (0, Isc), maximum power point (Vmp, Imp) and open-circuit (Voc, 0)

$$I = I_{pv} - I_o\left[\exp\left(\frac{V + R_s I}{aV_t}\right) - 1\right] - \frac{V + R_s I}{R_p} \quad (2)$$

Where

I_{pv} - photo current

I_o - cell saturation of dark current

V_t - Thermal voltage which is $V_t = kT/q$,

q - 1.6 x 10^{-19} C charge of an electron.

T - the cell's working temperature

a - an ideality factor

R_p - Shunt resistance

R_s - Series resistance

III. REPRESENTATION OF PV DEVICES

a. Solar Cell Model:

The basic equation (1) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array because they are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation and achieve the modified Eq 2, where I_{pv} and I_0 are the photovoltaic and saturation currents of the array and $V_t = N_s*k*T/q$ is the thermal voltage of the array with N_s cells connected in series. If the array is composed of N_p parallel connections of cells the photovoltaic and saturation currents may be expressed as: $I_{pv}=I_{pv,cell} * N_p$, $I_0=I_{0,cell} * N_p$. R_s is the equivalent series resistance of the array and R_p is the equivalent parallel resistance. This equation originates the I-V curve seen in Fig. 5, where short circuit (0, I_{sc}), maximum power point (V_{mpp}, I_{mpp}) and open-circuit (V_{oc}, 0) are highlighted. This Eq 2 is for Single Mode diode operation.

In Double diode model an extra diode attached in parallel to the circuit of single diode model. This diode is included to provide an even more accurate I-V characteristic curve that considers for the difference in flow of current at low current values due to charge recombination in the semiconductor's depletion region.

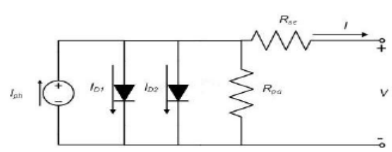

Fig 6: Double diode model

The accuracy of this model more than the single diode model but because of the difficulty to solve the equation, single diode model is preferred. The characteristic equation for double diode model is given by Eq 3 given below:

$$I = I_{ph} - I_{o1}\left[\exp\left(\frac{V + IR_s}{V_t}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V + IR_s}{aV_t}\right) - 1\right] - \left(\frac{V + IR_s}{R_p}\right) \quad (3)$$

The practical photovoltaic device has a series resistance R_s whose influence is stronger when the device operates in the voltage source region and a parallel resistance R_p with stronger influence in the current source region of operation. The R_s resistance is the sum of several structural resistances of the device .The R_p resistance exists mainly due to the leakage current of the *p-n* junction and depends on the fabrication method of the photovoltaic cell. The value of R_p is generally high and the value of R_s is very low and to simplify the model sometimes this parameters are neglected.

The amount of incident light directly affects the generation of charge carriers and consequently the current generated by the device. The light-generated current (I_{pv}) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine. Datasheets only inform the nominal short-circuit current ($I_{sc,n}$), which is the maximum current available at the terminals of the practical device. The assumption $I_{sc} \approx I_{pv}$ is generally used in photovoltaic models because in practical devices the series resistance is low and the parallel resistance is high. The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation:

$$I_{pv} = (I_{pv,n} + K_I \Delta T)\frac{G}{G_n} \quad (4.a)$$

And

$$I_{pv,n} = \frac{R_p + R_s}{R_p} I_{sc,n} \quad (4.b)$$

Where

$I_{sc,n}$ - Cell's short circuit current at STC (25^oC+1KW/ m ^{2})

K_1 - Cell's short circuit current temperature co-efficient.

ΔT - Difference between cell's reference temperature and actual cell's temperature.

G_n - Solar nominal irradiation in kW /m^2

G - Solar actual irradiation in kW /m^2

Ipv,n - Light-generated current at the nominal condition (usually 25 ◦C and 1000W/m^2)

The diode saturation current I0 and its dependence on the temperature may be expressed by:

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (5)$$

where E_g is the bandgap energy of the semiconductor ($E_g \approx 1.12$ eV for the polycrystalline Si at 25°C), and $I_{0,n}$ is the nominal saturation current:

$$I_0 = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{aV_t}\right) - 1} \quad (6)$$

Where

$V_{oc,n}$ - Cell's Nominal Open Circuit voltage,

K_V - Voltage/ temperature coefficient.

with $V_{t,n}$ being the thermal voltage of N_s series-connected cells at the nominal temperature T_n. The saturation current I_0 of the photovoltaic cells that compose the device depend on the saturation current density of the semiconductor (J_0, generally given in [A/cm^2]) and on the effective area of the cells.

In this method, we assume diode ideality factor =1.3. The value of the diode constant *a* may be arbitrarily chosen.

Usually $1 \le a \le 1.5$ and the choice depend on other parameters of the I-V model.

V. Simulation of Photovoltaic Array

The photovoltaic array can be simulated with an equivalent circuit model as in Fig 3. Two simulation strategies are possible. One is simulation of equivalent circuit model functional equations using Script Language of Simulator. Other one is simulation of equivalent circuit model blocks using Simulation Block function Generator. For this paper WSBYW03101693 solar array is simulated by MATLAB SIMULINK simulator. The parameter get from Datasheet is shown below:

TABLE I
ELECTRICAL CHARACTERISTICS DATA OF THE WS-140 (WSBYW03101693) SOLAR PANEL AT 25 °C, 1.5AM, 1000W/M2. TAKEN FROM THE DATASHEET

Parameters	Values
Maximum Power (Pmax)	140W
Voltage at Pmax (Vmp)	17V
Current at Pmax (Imp)	8.24A
Open-circuit voltage (Voc)	21V
Short-circuit current (Isc)	10A
(Ki)Temperature coefficient of Isc	(0.065 ± 0.015)%/°C
(Kv)Temperature coefficient of Voc	– (80±10)mV/°C
NOCT	47±2°C

By adjusting the equivalent circuit model from the given data in table 1 is shown in below mentioned table:

TABLE II
Electrical Characteristics Data Achieved From Table I

Parameters	Values
A	1.3
Rs	0.05Ω
Rp	100Ω
Io	7.89e-5A
Ipv	8.89A

Where R_s & R_p are achieved by iterative method by Newton raphson method. The circuit model composed of only one current source. The value of the current is obtained by numerically solving the I-V eq. 2. The solution of eq. 2 can be implemented by MATLAB SIMULINK as it has the feature of SimPowerSystems blockset as shown in fig 9. Figs. 11 and 12 show the P-V curves & I-V curve of the WS140 solar panel respectively simulated with the MATLAB/SIMULINK.

Table 1 is obtained from Datasheet specification of PV Panel and table 2 data are achieved by Model simulation process. For a PV cell with an ideal I-V characteristic, its open circuit voltage and short-circuit current are calculated as V_{OC} = 21V and I_{SC} = 10 A. The nonlinear nature of PV cell is apparent as shown in the figures, i.e., the output current and power of PV cell depend on the cell's terminal operating voltage and temperature, and solar insolation/ irradiation as well with increase of working temperature, the short-circuit current of the PV cell increases, whereas the maximum power output decreases. In as much as the increase in the output current is much less than the decrease in the voltage, the net power decreases at high temperatures. On the other hand, with increase of solar insolation/ irradiation, the short-circuit current of the PV module increases, and the maximum power output increases as well. The reason is the open-circuit voltage is logarithmically dependent on the solar irradiance, yet the short-circuit current is directly proportional to the radiant intensity. The temperature that the cells will reach when they are operated at open circuit in an ambient temperature of 20°C under AM 1.5 irradiance conditions with λ=0.8kW/m2 and a wind speed less than 1 m/s.

IV. SIMULATION RESULTS

In this paper a 140 watts Solar Photovoltaic Panel is modelled based on the electrical characteristics of the panels can provide information about the operational state of the system and for faults diagnostic in MATLAB/ Simulink environment as shown in fig 9. The irradiation and cell's working temperature is the two application dependent variables shown in fig 10. The Power vs Voltage and Current vs voltage output is given in fig 11 & 12 from which it is clearly observable that the open circuit voltage is achieved 21 volts, short circuit current is 10 amps, and maximum power is 140 watts for STC condition. A voltage of 17 volts and a current of 8 amps at maximum power point (MPP) are being derived from these figures for the proposed system which is satisfactory in result as compare to the data given for the actual 140 watts panel (WSBYW03101693) in table 1.

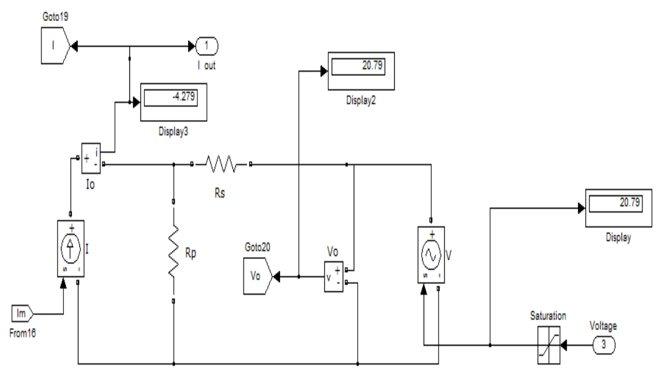

Fig 9: Subsystem implementation of generalized PV model

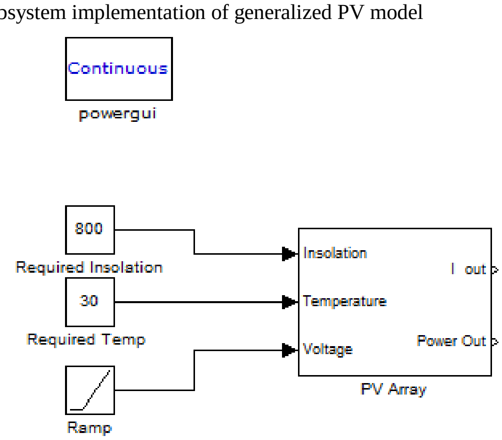

Fig 10: Generalized PV Model

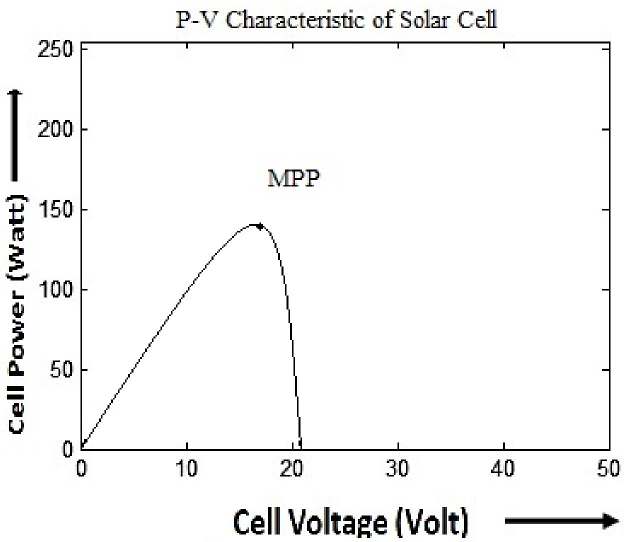

Fig11: P-V Plot of simulated Solar Module

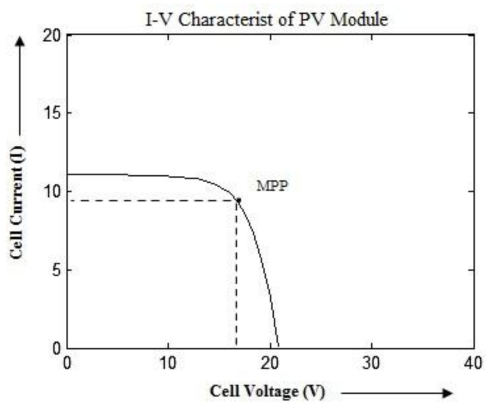

Fig 12: I-V Plot of simulated Solar Module

VI. CONCLUSIONS

A generalized PVmodel has been simulated using MATLAB/ Simulink tool. The simulation results show the nonlinearity of the array output. The I-V characteristic shows nearly constant current up to open circuit voltage and the P-V characteristic shows the power has maximum pick with respect to the voltage for particular environmental condition. With changing irradiation cell current changes linearly whereas cell voltage changes logarithmically which is clear from the simulation equations. With increasing temperature current increases up to a limit but due to short circuit current the voltage decreases 2.2 mV / ^{0}C. The proposed model can be applied in research activities in Solar energy application with maximum power point tracking (MPPT) scheme for grid interactive and off grid PV system.

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Snehamoy Dhar was born in West Bengal, India on April 14, 1987. He has received his B.Tech degree in Electronics & Communication Engineering in the year of 2009 from West Bengal University of Technology, Kolkata. He has two years of Industrial experience as an Assistant Project Engineer in Electrical Distribution project (RGGVY) in Meghalaya, India. He is presently pursuing his M.Tech degree in Power Electronics and Drives from SRM University, Chennai. His area of interest involves in Power Electronics, Solar photovoltaic Power system, Inverter, Harmonic analysis and reduction.

R.Sridhar was born in 1980 in Tamil Nadu, India. He received his B.E degree from Madurai Kamaraj University, Tamil Nadu in 2002 and the M.Tech degree in Power Electronics & Drives from SASTRA University in 2004. Presently he is pursuing his PhD degree in SRM University, Chennai, India. Currently he is an Asst. Professor in EEE Department in SRM University. His current research interests include Solar Energy (performance enhancement), Wind Electric Conversion Systems, Analysis of converters, and Electrical Machines. His research papers (7) have been presented in various/IEEE international/national conferences. He has one publication in International journal.

Varun Avasthy was born in Uttar Pradesh, India on August 26, 1988. He has received his B.Tech degree in Electrical & Electronics Engineering in the year of 2010 from Uttar Pradesh Technical University, Lucknow. He is presently pursuing his M.Tech degree in Power Electronics and Drives from SRM University, Chennai. His area of interest involves in Power Electronics, Grid Interactive Solar Photovoltaic Power system.