Abstract - Solar photovoltaic (PV) based electric power generation is gaining much importance due to huge availability of solar energy, developments in PV cell materials and energy transformation technology. Global warming effects and fast depletion of fossil fuels is directly encouraging this transformation process. The electric power produced by solar PV module depends on the insolation and temperature. This paper presents a mathematical model for a solar photovoltaic PV cell in order to evaluate its electrical characteristics with respect to weather conditions such as uniform insolation, change in insolation and change in temperature. The solar PV cell is modeled through mathematical equations and is represented by an equivalent circuit having a photocurrent source, a diode, a series resistor and a shunt resistor. As the performance of a solar PV array gets affected by PV array insolation and temperature, it is important to understand the relation between these effects and its dependence on the output electric power of PV array. The main purpose of this paper is to consider the effects of sunlight insolation and cell temperature, then output current and voltage (I-V) characteristics, output power and voltage (P-V) characteristics of PV model are simulated with help of Matlab simulation. This model is designed with a user-friendly icon and a dialog box like Simulink block libraries and it has been developed using Matlab/Simulink software package.

Keywords - Solar Cell Model, Solar Array Model, Solar Insolation, Maximum Power Point Tracker, Matlab, SIMULINK

I. INTRODUCTION

With increasing alarms about skyrocketing oil prices, depletion of fossil fuel, global warming and destruction to environment and ecosystem, the alternative solution for the above mentioned concerns is to be overcome, the only solution is the usage of alternative energy resources with high efficiency and low emission of gases.

The alternative energy resources are renewable energy sources are also called as non-conventional energy sources; these are continuously renewed by natural biological processes. These include solar energy, wind energy, ocean energy, tidal energy, geo thermal energy, hydropower, bio-energy - biomass, etc., are few examples of renewable energy sources. A renewable energy system transforms the energy found in sunlight, wind, sea waves, falling-water, geothermal heat, or biomass into required forms, such as in the form of electrical energy or heat energy.

In spite of the intermittency of sunlight, solar energy is broadly available and it is completely free of cost. A photovoltaic (PV) system converts solar energy into electrical energy. PV system is generally utilized in the forefront for electric power generation. It can generate direct current electricity without environmental pollution when exposed to solar radiation. PV systems are gaining more attention as renewable energy source as it does not pollute, has no fuel cost, doesn’t contain any moving parts, hence no operating noise, requires less maintenance costs, etc.,

The basic element of a PV system is a PV cell. A PV array consists of several cells connected in series and/or parallel for having a higher current/voltage rating of the PV array.

Model for a PV cell or a PV module based on the Shockley diode equation is presented [1], [2]. PV system sometimes may operate in conditions which results in non-uniform irradiance of PV arrays due to bird dropping, debris, dust, leaves, clouds, shadows etc., if number of PV cells are mismatched due to non-uniform irradiance, such cells will limit the output current of normal PV cells [7]-[10]. These operating conditions leads to reduction in output power, generation of hot spot and finally causes damage to the cell. To protect the PV cells a bypass diode is connected in parallel. To obtain maximum output from a PV system, it is very important to have the knowledge of PV cell characteristics under non-uniform irradiance [11]-[13].

The productivity of a PV array system depends on the working conditions. The current, output voltage and power of PV array fluctuate according to solar irradiation level, temperature and load current. These PV systems used as distributed generators (DG) and can be located at the places where the demand of electric energy ascends, thereby avoiding
losses of transmission and also contributing in reductions to the 
CO₂ emission. This paper presents Matlab-Simulink based PV 
module model, which can be series-parallelled to achieve 
require current-voltage rating of PV array.

II. PHOTOVOLTAIC MODELING

An ideal PV cell is modeled with a current source connected 
diode in anti-parallel. For a non-ideal PV cell, series resistance 
and a shunt resistance are connected. The value of series 
resistance is very small and that of a shunt resistance is very 
large. PV system displays a nonlinear I-V and P-V 
characteristics which fluctuate with the radiant intensity and 
operating cell temperature.

A. Mathematical model of a Photovoltaic Cell

Solar PV cell is a basic component of a PV system, it comprises 
of p-type and n-type semiconductors and is manufactured as a 
p-n junction on a thin wafer of semiconductor. The output of 
each PV cell is around 0.5V to 0.7V. When they are connected 
series, net output voltage increases and when connected in 
parallel, net output current increases.

There are many equivalent circuits for a PV cell, a 
single diode, a two diode model are mostly used. A single 
diode model being simple and accurate is taken up in this 
paper. The basic circuit of a single diode model for a solar PV 
cell [3]-[6] is shown in Fig. 2.

Fig. 2. Equivalent circuit of a single solar cell

The symbols for the above circuit are as follows:

- \( I_{ph} \): photo current
- \( I_{pv} \): output current
- \( I_{d} \): diode current
- \( I_{s} \): reverse saturation current
- \( I_{sh} \): shunt current
- \( I_{d,ref} \): reverse saturation current at reference temperature
- \( T \): reference temperature
- \( T_c \): cell operating temperature
- \( E_{g} \): band gap energy
- \( q \): charge of an electron = 1.6 * 10^-19 coulombs
- \( K \): Boltzmann’s constant = 1.3805 * 10^-23 J/K
- \( k_b \): temperature coefficient of short circuit current
- \( k_v \): temperature coefficient of open circuit voltage
- \( V \): voltage
- \( V_{pv} \): output voltage

\( V_{oc} \): open circuit voltage
\( V_{th} \): thermal voltage
\( R_{sc} \): series resistance
\( R_{sh} \): shunt resistance
\( N_{sc} \): number of cells in series
\( N_{sh} \): number of cells in parallel
\( S \): solar reference irradiation

The mathematical equations of a solar cell are given below.

Using Kirchoff’s first law

\[
I_{pv} = I_{ph} - I_{d} - I_{sh}
\]

(1)

\[
I_d = I_{d,ref} \left( \frac{V_{pv} + I_{ph} R_{sc}}{V_{th}} \right) - 1
\]

\[
I_{sh} = \frac{V_{pv} + I_{pv} R_{sh}}{R_{sh}}
\]

The load current \( I_{pv} \) is given as

\[
I_{pv} = I_{ph} - I_{d} - I_{sh} \left[ \frac{V_{pv} + I_{pv} R_{sh}}{R_{sh}} \right] - 1
\]

(2)

\[
V_{pv} = \frac{K T}{q}
\]

Photovoltaic cell characteristic curves, I-V, P-V curves are 
obtained by simulation equation (2).

B. Mathematical model of a Photovoltaic Module

A number of photovoltaic cells are connected in series-parallel 
to form an array, number of such arrays are further connected 
to form panels or modules. The solar PV system converts 
irradiation directly to electrical energy through photovoltaic 
effect. The Fig. 3 shows uniform insolation on a photovoltaic 
system.

Fig. 3. Uniform insolation for a photovoltaic system

The blocking diodes and bypass diodes are generally used in PV 
systems in series/parallel with PV arrays. A blocking diode allows 
flow of current from a PV panel to the battery for charging, i.e., 
storing energy during day time, but does not allow the current to 
flow back from the battery to the PV panel during night times, 
thereby preventing them from discharging. By pass diodes are 
connected in parallel with PV panels for a multi string PV panel.
The effect can be tuned in parallel with PV panels, and in such case, the bypass diode helps in operating the whole solar PV system. These bypasses the path of the current from the shaded panel and provides an alternate path for the current flow and hence maintaining continuity of power supply. Based on single PV cell circuit module, the voltage and current relationship of a PV module can be represented as (3).

\[
I_{PV} = N_{Sh}I_o - N_{Se}I_o \left[ \exp \left( \frac{V_{PV} - \frac{N_{Sh}I_o + I_{PV}R_o}{N_{Se}}}{aV_o} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_o}{R_m}
\]

(3)

C. Photovoltaic Cell/module under Non-Uniform Insolation

Under uniform insolation, Eq. (3) is able to precisely model the performance of PV module. But for non-uniform insolation, i.e., under partial shading condition Eq. (3) cannot simulate this weather condition. The Fig. 4 shows non uniform insolation on a photovoltaic system. This non uniform insolation may occur due to various factors like bird droppings, passing of aeroplane, clouds, etc. The shaded PV arrays signify that solar insolation on them is less or nil as compared to the shaded PV array, hence their output power is either low or zero. To maintain the continuity of power production all the PV panels have bypass diodes connected in parallel with PV panels, and in such case these types of panels are eliminated and the flow of current follows the bypass diode, hence maintaining continuous power production. The bypass diodes also prevent the flow of current from uniform insolated PV panel which are at higher potential to the less insolated or shaded PV panel which is at a lower potential. Hence, even under non uniform insolation condition the bypass diode helps in operating the whole solar PV system and produce electricity at a lower rate.

III. PV MODULE MODEL IN MATLAB-SIMULINK

A 175W PV module BP-4175B has been chosen for modeling in Matlab-Simulink environment. The concerned electrical characteristics specifications are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>400 W</td>
</tr>
<tr>
<td>Voltage at maximum power</td>
<td>32.5 V</td>
</tr>
<tr>
<td>Current at maximum power</td>
<td>13.94 A</td>
</tr>
<tr>
<td>Short-circuit current</td>
<td>15.5 A</td>
</tr>
<tr>
<td>Open-circuit voltage</td>
<td>38.6 V</td>
</tr>
<tr>
<td>Temperature coefficient of open-circuit voltage</td>
<td>0.065 %/°C</td>
</tr>
<tr>
<td>Temperature coefficient of short-circuit current</td>
<td>-0.5 %/°C</td>
</tr>
</tbody>
</table>

IV. SIMULATION RESULTS

This section presents the simulation results of the PV cell at different weather conditions like constant temperature at different insulations and constant insolation at different temperatures. Also the simulation results of the PV cell at non-uniform insolation are presented.

A. Illustration- I (uniform insolation)

For a single PV module, the I–V, P–V characteristics at uniform insulations are presented below. The I–V, P–V curves at a constant temperature of 25°C but at different insolation levels are shown in Fig. 5 & Fig. 6 respectively. The solar insulations are 1000W/m², 800W/m², 600W/m², 400W/m², and 200W/m² respectively.

The I–V, P–V curves at a constant insolation of 800 W/m² and at different temperatures are shown in Fig. 7 & Fig. 8 respectively. The temperatures are 25°C (298° K), 35°C (308° K) and 45°C (318° K) respectively.

As the effects of non-uniform insolation on a solar module cannot be obtained from mathematical model i.e., Eq. (3), the solar photo current is used which is denoted by a current source and the effects can be simulated by changing the values of current source.
The I–V, P-V curves at non-uniform insolation at two different insolation of 800 W/m² and 500 W/m² at a constant temperature of 40°C (313 K) is shown in Fig. 9 & Fig. 10 respectively.

The simulation not only just gives I-V and P-V characteristics, i.e., the behavior of PV array, but also its study helps in developing electronic circuit for maximum power point tracker for tracking maximum power from P-V characteristics where the system needs to operate, hence new MPPT strategies can be developed. The presented results will help in designing best configuration of PV array to produce maximum output power.

REFERENCES

V. CONCLUSION
A PV module model simulation using MATLAB-Simulink software is presented in this paper. Using this model I-V and P-V characteristics can be studied with different weather conditions of insolation and temperature, i.e., under uniform and insolation non-uniform insolation. When PV modules are exposed to non-uniform insolation, multiple peaks in I-V, P-V characteristics are formed. If the PV system has to operate at maximum efficiency, it needs to track the power at global peak and hence should be able to discriminate between local peak and global peak.

The conclusion drawn from the simulation results are as follows:

i. During uniform insolation of a PV modules, there exists only one peak for each I-V and P-V characteristics
ii. During non-uniform insolation of a PV modules, there exists multiple peaks for both I-V and P-V characteristics
iii. The number of power peaks are directly proportional to number of insolation levels on PV modules, during non-uniform insolation of a PV modules.
iv. During non-uniform insolation of a PV modules, the output power produced is more for the same series string.
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