A Novel Approach of Photovoltaic Module Modeling

ISSN 2319-9725

Seha Gupta  
Electrical & Electronics Deptt.  
YMCA University of Science & Technology  
Faridabad, Haryana, India

Dr. Rashmi Jain  
Electrical Deptt.  
YMCA University of Science & Technology  
Faridabad, Haryana, India

Abstract: In this work, Matlab/Simulink environment is used to develop the mathematical model of a photovoltaic module with the help of standard equations of a photovoltaic cell including the effect of solar irradiation and cell temperature. The PV model has a nonlinear i-v characteristic and its maximum power (MP) point varies with solar insolation. In this paper, one-diode model of a PV solar cell is taken and considers the series and shunt resistances and simulates the effects of various parameters such as temperature, irradiance and PV voltage. A maximum power point tracking (MPPT) technique is used to operate the PV module at its maximum power point as the solar irradiation is a variable quantity. The main objective is to find the best I-V equation for the single-diode photovoltaic (PV) model and to verify the simulator using 36W PV module.

Keywords: Matlab/Simulink, Photo-Voltaic module, PV model parameters, irradiance, PV-IV Curves.
1. Introduction:

The concentration on the use of fossil fuels for energy supply is the main threat for the stability of the global climate system and our natural living conditions. To conserve our globe, the scientific community gave evidence that mankind has to decrease the greenhouse gases emissions, mainly CO2 and methane, by 60 - 70\% as a minimum until the year 2050 [1]. In order not to harm our natural living spaces and threaten their resilience, a renewed compatibility would require a suitable form of energy alternative sources that should be independent, easily accessible, and low in cost and should be environmentally clean. Renewable energy, and in particular power generation from solar energy using Photovoltaic (PV) has emerged in last decades since it has the aforesaid advantages and less maintenance, no wear and tear.

Photovoltaic cell, the basic device of photovoltaic system, converts solar energy into electrical energy. Group of PV cells is known as a PV module or Panel. Panels can be grouped to form large photovoltaic arrays. Solar system is the most important renewable and sustainable energy system. Depending on the semiconductor and the built-up technology, a PV cell generates a voltage around 0.5 to 0.8 volts. Since the value is too small for practical usage, PV generation systems usually consist of PV Panels (a series-parallel combinations of PV cells) in order to obtain the required voltage and current output. To feed the load, this DC power has to be converted to AC at standard power frequency with the help of sophisticated inverter systems that keeps the AC output voltage at the specified level in spite of the variation of the DC voltage with variation of solar irradiance $E$ (W/m$^2$) and ambient temperature $T$ (°K).

For electricity users from utility grid, photovoltaic system have not been an attractive alternative due to their initial high cost, even after considerable decay in PV cell prices due to new developments in the manufacturing process. But as an expensive choice PV arrays are still widely considered. After building such an expensive renewable energy system, the user naturally wants to operate the PV array at its highest energy conversion output by continuously utilizing the maximum available solar power of the array. The electrical system powered by solar arrays requires 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 [2]. Among prominent Cell technology Monocrystalline, Polycrystalline and thin Film technologies e.g.
amorphous silicon (a-Si), copper indium diselenide (CuInSe2) and cadmium telluride (CdTe) are commercially available. The monocrystalline and polycrystalline are based on costly microelectronic manufacturing process and their sunlight to electrical efficiency varies from 10%-15% for monocrystalline and 9%-12% for polycrystalline cells. Among Film Cell technology, a-Si has $\eta=10\%$, CuInSe2 has $\eta=12\%$, and CdTe has $\eta=9\%$ [3]. Other novel technologies such as thin layer silicon and dye-sensitized nano-structured materials are in early development stage and have $\eta=9\%$. The monocrystalline PV Cell/module has best efficiency among all commercially available technology and therefore is a focus of present study[4].

In 2010 solar photovoltaic power (PV) was the leading renewable energy technology in terms of new capacity growth by almost 13,000 MW in Europe [5]. The main applications of PV system come in either grid-connected (power plants, hybrid system) or standalone (water pumping, electric vehicles, military and space applications) configurations. Several modelling studies on photovoltaic and MPPT technology have been conducted. Gow [6], employed fuzzy logic control to find the maximum power point tracking (MPPT) for both PV and wind energies. Tsai [7] implemented an insulation-oriented PV model using Matlab/Simulink.

Figure 1 shows the photocurrent generation principle of PV cells. In fact, when sunlight hits the cell, the photons are absorbed by the semiconductor atoms, freeing electrons from the negative layer. This free electron finds its path through an external circuit toward the positive layer resulting in an electric current from the positive layer to the negative one.

![Figure 1: Photocurrent generation principle](image-url)
2. PV Modelling:

Solar cell, a p-n junction that in charge of transforming the sun rays or photons directly into electric power, is the basic building block of a PV Array. It has an equivalent circuit as shown in Figure 2:

![Single diode equivalent circuit of a PV Cell](image)

Figure 2: single diode equivalent circuit of a PV Cell

The process of modeling the solar cell can be developed based on being the net current of the cell, the difference of the photocurrent $I_{ph}$, (the current generated by the incident light, directly proportional to the sun irradiation) and $I_d$ (the normal diode current). Therefore, the ideal solar cell can be modelled as a current source in anti-parallel with a diode. Improving the PV cell model includes the effects of series and shunt resistance. The value of $R_{sh}$ is very large and that of $R_s$ is very small, hence they may be neglected to simplify the analysis. The PV mathematical model used to simplify our PV array is represented by the equation:

$$I = NpI_{ph} - NpI_{ Rs}[\exp\left(\frac{q}{kT} \cdot \frac{V}{N_s}\right) - 1]$$

Where; $V = V_{ph} + I_{ph}R_s$

Where

$I$ is the PV array output current

$V$ is the PV array output voltage

$N_s$ is the number of cells in series

$N_p$ is the number of cells in parallel

$q$ is the charge of an electron $= 1.6 \times 10^{(-19)}$ C
k is the Boltzmann’s constant = 1.3805 × 10⁻²³ J/K

A is the p-n junction ideality factor

T is the cell temperature (K)

Irs is the cell reverse saturation current at 25°C and 1000W/m² = 2.55A

The factor A in above equation determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1 to 5 but for our case A=2.46 [8].

The cell reverse saturation current Irs varies with temperature according to the following equation:

\[ I_{rs} = I_{rrs} \left( \frac{T}{T_r} \right)^{3.3} \exp\left( \frac{-qE_g}{KA \left( \frac{1}{T_r} - \frac{1}{T} \right)} \right) \]

Where

Tr is the cell reference temperature

Irr is the cell reverse saturation temperature at Tr and

EG is the band gap of the semiconductor used in the cell

The temperature dependence of the energy gap of the semiconductor is given by [9]:

\[ E_g = E_g(0) - \frac{\alpha T^2}{T + \beta} \]

The photo current Iph depends on the solar radiation and cell temperature as follows:

\[ I_{ph} = [I_{scr} + K_i(T - T_r)]S/100 \]

Where;

Iscr is the cell short-circuit current at reference temperature and radiation,

Ki is the short circuit current temperature coefficient, and

S is the solar radiation in mW/cm².

The PV power can be calculated using first equation as follows:

\[ P = IV = NpI_{ph}V \left( \frac{q}{KT_A} \cdot \frac{V}{N_s} \right) - 1 \]
For computer simulation of a physical system modeling should be done. It includes all the physical elements & all the parameters influencing the system. In this modeling the physical system is converted to computer codes and characteristics are plotted. To describe the behavior of the physical PV cell, the PV model is chosen by the researchers. Most commonly used model is a single diode model. The single diode model is as shown in figure 2.

3. A PV Cell Model:

A simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the solar energy (photons) that hits on the solar cell (photocurrent Iph). During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is allowed to connect to an external source (large voltage) it generates a current Id, called diode (D) current or dark current. The diode determines the IV characteristics of the cell.

The circuit diagram of a PV cell is shown above in Fig 2. Accurate simulation is obtained after considering the following parameters:

1. Temperature dependence of the diode reserved saturation current Is.
2. Temperature dependence of the photo current Iph.
3. Series resistance Rs [9] (internal losses due to the current flow) which gives a more accurate shape between the maximum power point and the open circuit voltage.
4. Shunt resistance Rsh [10], in parallel with the diode, this corresponds to the leakage current to the ground.

The parallel resistor Rp characterizes the leakage current on the surface of the cell due to the non-ideality of the PNjunction an impurities near the junction. The series resistor Rs represents the various contact resistances and the resistance of the semiconductor. Current and voltages are:
### Table 1: Electrical characteristics data of Solkar PV module:

<table>
<thead>
<tr>
<th>Description</th>
<th>ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>37.08W</td>
</tr>
<tr>
<td>Voltage at maximum power (Vmp)</td>
<td>16.56V</td>
</tr>
<tr>
<td>Current at maximum power (Imp)</td>
<td>2.25A</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>21.64V</td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
<td>2.25A</td>
</tr>
<tr>
<td>Total number of cells in series (Ns)</td>
<td>36</td>
</tr>
<tr>
<td>Total number of cells in parallel (Np)</td>
<td>1</td>
</tr>
</tbody>
</table>

4. **PV Model Equation**

One can obtain the following mathematical model of a PV cell from an equivalent circuit diagram:

\[
I_{pv} = NpI_{ph} - Np \cdot I_0 \left[ \exp \left( q \cdot V_{pv} + \frac{I_{pv}R_S}{N s A K T} \right) - 1 \right]
\]

Where:

- \( I_{pv} \) is output current of a PV module (A)
- \( V_{pv} \) is output voltage of a PV module (V)
- \( T \) is the module operating temperature in Kelvin
- \( I_{ph} \) is the light generated current in a PV module (A)
- \( I_0 \) is the PV module saturation current (A)
A = B is an ideality factor = 1.6

k is Boltzmann constant = 1.3805 × 10^-23 J/K

q is the Electron charge = 1.6 × 10^-19 C

R_S is the series resistance of a PV module

N_S is the number of cells connected in series.

N_P is the number of cells connected in parallel.

Fig 3 shows the photovoltaic module in Matlab/Simulink according to the standard equations of PV Cell.

![Figure 3: PV Module in Matlab/Simulink](image)

5. Solar Cell Characteristics:

Solar cells naturally exhibit a nonlinear I-V and P-V characteristics which vary with solar irradiation and cell temperature. The fundamental parameters related to solar cell are short circuit current (I_SC), open circuit voltage (V_OC) and maximum power point (MPP). The typical I-V and P-V characteristics of solar cell are shown in figure 4,

![Figure 4: Typical I-V and P-V characteristics of solar cell](image)
6. Results:

The model of the PV module was implemented using a Matlab Simulink model. The model parameters are evaluated during execution using the equations listed as in the previous sections. The PV module chosen for this simulation provides 36W nominal maximum power and has 36 series connected cells. The parameter specification of the module is as shown in Table-1. The model was built in stages step by step to finalize the model. The subsystem contains all the mathematical equations of every stage model block.

The I-V and P-V curves for various irradiance values but a fixed temperature (25°C) are shown below in Figure 5&6. It is depicted that the PV output current varies drastically with insulation conditions and there is an optimum operating point such that the PV system delivers its maximum possible power to the load. The optimum operating points changes with the solar insulation, temperature and load conditions.

The characteristic I-V curve tells that there are two regions in the curve: one is the current source region and another is the voltage source region. In the voltage source region (in the right side of the curve), the internal impedance is low and in the current source region (in the left side of the curve), the impedance is high. Irradiance temperature plays an important role in predicting the I-V characteristic, and effects of both factors have to be considered while designing the PV system. Whereas the irradiance affects the output, temperature mainly affects the terminal voltage.

From the I-V, we observe that the short circuit current increases with increase in irradiance at a fixed temperature. Moreover, from the I-V and P-V curves at a fixed irradiance, it is observed that the open circuit voltage decreases with increase in temperature.

I-V and P-V characteristics under varying irradiation with constant temperature are obtained as shown in Figures 5 to 8. Between 0 and 1 s, the irradiation is 200W/m2, between 1 and 2 s it is 600 W/m, while from 2 s onwards it is 1000W/m2.
When the operating temperature increases, the current output increases marginally but the voltage output decreases drastically, which result in net reduction in power output with a rise in temperature.

From the graphs when the irradiance increases, the current and voltage output also increases. This result shows the net increase in power output with an increase in irradiance at the constant temperatures. Furthermore, it is well known that for a certain PV panel, the voltage-power characteristics are fixed for each insolation without intersection, as shown in Figure-5. Hence, for any given PV voltage and power, the corresponding insolation can be estimated.
Figure 7: VPV photovoltaic voltage:

Figure 8: Signals for Insolation & temperature:

Figure 9: PV Current:

Figure 10: PV Power:
7. Conclusion

The step-by-step procedure for modeling the PV module is presented. This mathematical modeling procedure serves as an aid to induce more people into photovoltaic research and gain a closer understanding of I-V and P-V characteristics of PV module. In section II, Equation for PV Array and figure-2, it can be seen that the PV current \( I_{SC} \) is a function of the solar irradiation and is the only energy conversion process in which light energy is converted to electrical energy. Equations for module saturation current indicate that PV voltage is a function of the junction voltage across the diode, which is the material property of the semiconductors, susceptible to failure at higher temperatures. The physical equations governing the PV module (also applicable to PV cell) is elaborately presented with numerical values of module saturation current at various temperatures. Hence, this circuit model presents the relationship between module parameters and circuit performance. This involves the step-by-step method for the PV modeling in Matlab Simulink. This work provides a clear and concise understanding of the, I-V and P-V characteristics of PV module, which will serve as the model for researchers and expert in the field of PV modeling. The open circuit P-V, P-I, I-V curves we obtained from the simulation of the PV array designed in MATLAB environment explains in detail its dependence on the irradiation levels and temperatures. The entire energy conversion system has been designed in MATLAB-SIMULINK environment. The various values of the voltage and current obtained have been plotted in the open circuit I-V curves of the PV array at insolation levels of 100 mW/cm\(^2\) and 80 mW/cm\(^2\). The voltage and current values lie on the curve showing that the coupling of the PV array with the boost converter is proper. However the performance of the photovoltaic device depends on the spectral distribution of the solar radiation.
References: