A New Approach for Modeling of Photovoltaic Cell/Module/Array Based-on Matlab

M. Toghyani Rizi, M. H. Shahrokh Abadi*

Faculty of Electrical and Computer Engineering, Hakim Sabzevari University, Sabzevar, Iran

Abstract

A step-by-step mathematical modeling of one-diode equivalent circuit of photovoltaic cell/module, implemented in matlab/simulink was developed. The model was designed to take different inputs in terms of voltage, insolation, temperature, series and parallel resistances to simulate the electrical behaviour of the module and to produce V-I and P-V curves. The novelty of this work is consideration the effects of series and parallel resistances of the model as the independent inputs. Furthermore, hot spot heating and bypass diode operation of the module were investigated. Finally, using the proposed model, a photovoltaic array in parallel mode was developed and simulated.

Keywords

Photovoltaic Cell, Module, MATLAB, Simulink, Series Resistance, Parallel Resistance, I-V Curve, P-V Curve

1. Introduction

Solar energy has the advantage of being environmentally friendly, pollution free, cost-efficient, and generally is unlimited in availability [1-4]. All these factors and dimensions of solar energy have attracted the attention of many researchers toward the photovoltaic (PV) systems and devices. The market for PV systems is growing worldwide [5]. Today’s solar PVs provide nearly 4800 GW. Between 2004 and 2009, grid connected PV capacity reached 21 GW with an increasing rate of 60% annually [5]. However, studies on the characteristics of a PV system are frequently analyzed through the use of a CAD model, which is always going to be a big challenge for solar cell systems and has been concerned by many researchers [6-8].

There are common and simple models of solar panel that have been developed and integrated to software, e.g. Matlab. Extensive works exist in literature about modeling solar power generation by photovoltaic cell [9-11]. In 2011, a 36 W PV module for simulation purposes, called Solkar, has been developed by Pandiarajan and Muthu [12], in which, the effects of series and parallel resistances of PV module, as independent inputs, have not been considered in the model. In this paper, a step-by-step procedure for simulating PV module using subsystem blocks, with user-friendly icons of Matlab/ Simulink block libraries is developed in six steps. In section 2, the mathematical relationships between PV cell parameters, the modeling procedure, and simulation scenarios have been presented. Simulation results respect to the inputs alteration have been given in section 3. In section 4, the PV array has been presented and simulated followed by conclusion in section 5. It will be shown that a major improvement to realize the PV characteristics has been done by implementation of a new equation for output current, \( I_{pv} \). Also inserting a delay block to resolve an algebraic loop error due to the simulation is the other superior of the current work. Another novelty of the presented model is building a PV array based-on the improved PV module in parallel mode. Hot spot heating effect and bypass diode operation is also added to accomplish the work.

* Corresponding author
E-mail address: mhshahrokh@ieee.org (M. H. S. Abadi), toghyani.rizi@gmail.com (M. T. Rizi)
2. Model for the PV Module

2.1. Analytical Model

A one-diode equivalent circuit of solar cell (Fig. 1) has been considered as the basis model through this work. In this model, \( I_{ph} \) represents the current generated by the photons and does not change when temperature and incident radiation of light are constant. Losses have been introduced by adding a series and a parallel resistance, \( R_s \) and \( R_p \), respectively, with regard to the internal cell resistances, contact resistances, and the effect of leakage currents. Also, \( I_D \), \( I_{pv} \), and \( V_{pv} \) correspond to the diode current, the output current, and the terminal voltage, respectively \[13\]. A solar panel has been formed by using \( N_s \) and \( N_p \) number of the solar cell put in series and parallel to fulfill the required power. For the simulation the SOLKAR 36 W PV module has been considered as the reference module. The electrical parameter of this module has been given in Table 1 \[14-15\].

![One-diode equivalent circuit of solar cell.](image1)

![A typical module has 36 cells connected in series.](image2)

![Model of solar panel consists of \( N_s \) and \( N_p \) number of series and parallel cells.](image3)

Table 1. Electrical parameters of SOLKAR 36w PV module* \[15\].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power, W</td>
<td>37.08</td>
</tr>
<tr>
<td>Voltage at Maximum Power ( (V_{MP}) ), V</td>
<td>16.56</td>
</tr>
<tr>
<td>Current at Maximum Power ( (I_{MP}) ), A</td>
<td>2.25</td>
</tr>
<tr>
<td>Open Circuit Voltage ( (V_{oc}) ), V</td>
<td>21.24</td>
</tr>
<tr>
<td>Short Circuit Current ( (I_{sc}) ), A</td>
<td>2.55</td>
</tr>
<tr>
<td>Total Number of Cells Connected in Series ( (N_s) )</td>
<td>36</td>
</tr>
<tr>
<td>Number of Cells Connected in Parallel ( (N_p) )</td>
<td>1</td>
</tr>
</tbody>
</table>

* The electrical specifications have been given at irradiance of 1 kW/m² and cell temperature of 25°C.

Considering the following parameters and definitions, the photovoltaic array can be described through the equations 1 to 5 as it follows \[16-17\]:

\[
V_{pv} = \text{output voltage of a PV module (V)}
\]

\[
I_{pv} = \text{output current of a PV module (A)}
\]

\[
T_{ref} = \text{the reference temperature} = 300 \, ^\circ\text{K}
\]

\[
I_{ph} = \text{the light generated current in a PV module (A)}
\]

\[
I_0 = \text{the PV module saturation current (A)}
\]

\[
A = \text{an ideality factor} = 1.6
\]

\[
k = \text{the Boltzmann constant} = 1.3805 \times 10^{-23} \frac{J}{k}
\]

\[
q = \text{Electron charge} = 1.6 \times 10^{-19} C
\]

\[
R_s = \text{the series resistance of a PV module}
\]

\[
R_p = \text{the parallel resistance of a PV module}
\]

\[
I_{SC} = \text{the PV module short-circuit current at 27 \, ^\circ\text{C}} \text{ and } 1\text{kw/m}^2 = 2.55A
\]

\[
k_i = \text{the short-circuit current temperature co-efficient at } I_{SC} = 0.0017/C
\]

\[
\lambda = \text{the PV module illumination (kw/m^2)}
\]

\[
E_{g0} = \text{the band gap for silicon} = 1.1\text{eV}
\]

\[
N_s = \text{the number of cells connected in series}
\]

\[
N_p = \text{the number of cells connected in parallel}
\]

The module photo current:

\[
I_{ph} = [I_{SC} + K_i(T_{ak} - T_{ref})]\lambda
\]

The module reverse saturation current, \(-I_{pv}\):
Module saturation current variations due to the temperature fluctuations is calculated from:

\[
I_n = I_{sc} \exp \left( \frac{qV_n}{NskAT_{ak}} \right) - 1
\]  

(2)

The output current of PV cell can be determined by KCL at the input node, given as:

\[
I_p = I_{ph} - I_n \exp \left( \frac{qE_{ST}}{kT_{ak}} \left( \frac{1}{T_{ref}} - \frac{1}{T_{ak}} \right) \right) - \frac{V_p + I_{ph}R_p}{R_p}
\]  

(3)

Therefore, the equation for the current and voltage terminal of the array becomes:

\[
N_i = N_sI_{ph} - N_sI_n \exp \left( \frac{q}{NskAT_{ak}} \left( \frac{V_p}{N_s} + \frac{I_{ph}R_p}{N_p} \right) \right) - 1
\]

(5)

where \( V_{ph} = V_{oc}, N_p = 1 \) and \( N_s = 36 \).

2.2. Simulink Modeling

Using the Matlab/Simulink simulation tool, the model of photovoltaic cell implemented as it has been presented in Fig. 3. The model consists of a direct implementation of the analytical expressions described above as six subsystems. A step by step procedure of model illustration to create these subsystems has been given in detail.

**Step1:** In this step a subsystem to convert Celsius degrees to Kelvin has been implemented and given in Fig. 4. The basic equations for the conversion are:

Operating Temperature:

\[
T_{ak} + Temp = T_{ak} = 273 + Temp
\]

(6)

Reference Temperature:

\[
T_{ak} + T_{ref} = T_{ak} = 273 + 27 = 300
\]

(7)

**Step2:** Using equation (1), in this step, \( I_{ph} \) has been carried out based on the inputs given in Fig. 5. The parameters used in this step are:

Insolation \( \lambda - \left( \frac{kW}{m^2} \right) \)

Module operating temperature, \( T_{ak} = 30 \) to 70°C

Module reference temperature, \( T_{ak} = 27°C \)

Short circuit current (\( I_{sc} \)) at reference temp = 2.55A

Fig. 3. Implemented model of PV module.

Fig. 4. (a) Block diagram of °C to °K subsystem1, (b) Internal circuit of subsystem1.
Fig. 5. (a) Block diagram of subsystem 2, (b) Internal circuit of subsystem 2.

Fig. 6. (a) Block diagram of subsystem 3, (b) Internal circuit of subsystem 3.
Step 3: This block uses short circuit current of $I_{SC} = 2.55\, \text{A}$ as the input at reference temperature and module reference temperature of $T_{rk} = 27\, ^\circ\text{C}$ and then calculates the $I_v$ based on the Equation (2). The subsystem has been described in Fig. 6.

Step 4: In this step, saturation current, $I_s$, has been calculated using the reverse saturation current, $I_{rs}$, the module reference temperature, $T_{rk} = 27\, ^\circ\text{C}$, and the module operating temperature, $T_{ak}$, with respect to the Equation (3). The detail of this subsystem has been given in Fig. 7.
Fig. 8. (a) Block diagram of subsystem 5, $kT_{st}$, (b) Internal circuit for the block.

Fig. 9. (a) Block diagram for the subsystem 6 to calculate $I_{pv}$, (b) Internal circuit for this block.
Step5: In this subsystem, operating temperature in Kelvin, $T_{ak}$, is taken to calculate $kAT_{ak}$, a parameter used in the Equations (4) and (5).

Step6: This block executes an internal function, $Fcn$, to carry out the $I_{pv}$. The function has been given based-on previously defined $I_{pv}$ in the Equation (5):

\[
Fcn = u(3) - \exp\left(\frac{u(2)}{36}(u(1) + u(6)) - 1\right)u(4) - \left(\frac{u(1)}{36} + u(6)\right)u(5)
\]

where each unit block of $u(1)$ through $u(6)$ have been illustrated in Fig (7). It is important to mention that in this block the effect of both series and parallel resistances have been considered. Also, through this work 36 cells in series ($N_s = 36$) has been considered in one row ($N_p = 1$) as a module. While performing the $Fcn$ in the Matlab, an algebraic loop warning is appeared in the command window, which was solved by inserting a delay block in the feedback loop coming from the output $I_{pv}$ before entering the exponential block so that the current value can be calculated based on its previous values.

Step7: The final step is interconnection of all the six previously defined subsystems to implement the whole PV module, given in Fig. 3. The block diagram of the module has been given in Fig. 10.

2.3. Simulation Scenarios

Examining the outputs of a PV system include the instantaneous power and current characteristics. These parameters are altered by the input parameters of: solar insolation, temperature, voltage, series and parallel resistances as shown in the Fig. 11. All these inputs, except for the $V_{in}$ (repeating sequence), are created by signal builder blocks. A multiplexer is used to collect the results produced by simulation into a variable “$Vout$” that is used later to plot the different curves under Matlab command mode.
3. Results and Discussions

3.1. Effect of Alteration of Sunlight Irradiation

I-V and P-V characteristics of the module have been obtained and shown in Fig. 12 under different irradiation of $\lambda = 0.2$, 0.6, and 1 $kW/m^2$, at 27°C, using series and parallel resistances of 0.1 Ω and 100 Ω, respectively.

It can be seen from Fig. 12(a) that an increment in the insolation from 0.2 to 1, causes a significant increasing in the maximum available power, $P_m$, from 7 to 40 watts, respectively. Correspondingly, graph in Fig. 12(b) shows a proportional relationship between the short-circuit current and the incident sunlight by a ratio of 5, at any voltage less than 15 V, which enunciates that the PV-cell behaves more like a current source than a voltage source [17].

![Fig. 12](image1.png)

**(a)**

![Fig. 12](image2.png)

**(b)**

Fig. 12. (a) P-V vs. (b) I-V curves of the module under different values of incident sunlight.

3.2. Effect of Temperature Variation

Fig. 13 shows the current versus voltage and the power versus voltage characteristics of the module at temperatures of 25°C, 50°C, and 75°C, where the sunlight irradiation has been fixed at 1 $kW/m^2$ and fixed series and parallel resistances of 0.1 Ω and 100 Ω, respectively. The figure shows that any increase in the temperature causes a decrement in the maximum power, $P_m$. This is due to an increment in the saturation current, $I_0$, given in Equation (3), when the temperature is increased. Furthermore, the short circuit current remains almost constant when the temperature is changed at voltages up to 13 volts.

3.3. Effect of Series Resistance, $R_s$

The simulation was run at different values of $R_s = 0$, 0.4, and 1 Ω, and the related graphs of V-I and P-V characteristics have been obtained as shown in Fig. 14. The results show a great impact of series resistance of the module on the slope of the I-V curve at the voltages almost near the open-circuit voltage, $V_{oc}$. Degradation in the cell current due to greater values of $R_s$ indicates more power dissipation.

![Fig. 13](image3.png)

**(a)**

![Fig. 13](image4.png)

**(b)**

Fig. 13. (a) P-V vs. (b) I-V curves of the module at temperatures of 25°C, 50°C, and 75°C.
An important parameter of PV cells is called fill factor (FF), which in conjunction with $V_{oc}$ and $I_{sc}$ determines the maximum power from a solar cell, and can be calculated from:

$$FF = \frac{P_{max}}{V_{oc} I_{sc}}$$

(9)

Fig. 14(a) also demonstrates that the output power of cell is reduced at higher values of $R_s$, resulted in lower FF.

3.4. Variation in Shunt Resistance, $R_{sh}$

An alternate current path, rather than the output current, is produced when the PV cell is distracted from the ideal condition. This digression is due to the shunt resistance. Such a diversion reduces the amount of current flowing through the solar cell junction and considerably reduces the voltage from the solar cell. A simulation is produced at different values of shunt resistance, $R_{sh} = 1, 10,$ and $1000 \Omega$ and V-I and P-V characteristics of the cell were obtained as shown in Fig. 15. It is clear that when the $R_{sh}$ is lowered the output current of PV cell is diminished steeply, indicates more power dissipation which can be translated into Fill Factor lowering. To achieve higher output power and Fill Factor, for any applicable PV cell, $R_{sh}$ must be increased while the $R_s$ must be decreased, simultaneously.

3.5. Hot Spot Heating Effect and Bypass Diode Operation

Hot-spot heating occurs when there is one low current solar cell in a string of at least several high short-circuit current solar cells, as shown in the Fig. 16 [13, 18, 19].

One shaded cell in a string reduces the current through the “good” cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell. Hot-spot heating occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. Essentially the entire generating capacity of all the good cells is dissipated in the poor cell. The enormous power dissipation occurring in a
small area results in local overheating, or “hot-spots”, which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell. The destructive effects of hot-spot heating may be circumvented through the use of a bypass diode. A bypass diode is connected in parallel, but with opposite polarity, to a solar cell as shown below [20-22].

The operation of the bypass diode has been considered by implementing a Simulink model, given in Fig 18(a), using the Equation (10):

\[ V_{\text{bypass}} = -V_i \ln \left( \frac{I_{\text{bypass}}}{I_0} + 1 \right) \]  

(10)

Where \( V_i = 25 \, mV, I_0 = 1 \, \mu A \)

The decision for being a diode in circuit or not is taken by Switch1. The Diode = 0 is referred to as no bypass diode, then the output voltage of PV is switched for the simulation, which means the PV operates normally. If Diode signal is “1” and \( V_{pv} < V_{\text{bypass}} \) then the diode is forward biased and \( I_{\text{bypass}} \) versus \( V_{\text{bypass}} \) curve can be obtained (Fig. 18(b)). The function of saturation block is to rectify the crossing current because bypass diode current cannot be negative. For the modeling, it has been assumed that the hot spot heating has been occurred and \( V_{pv} = -1 \, V \). A scope observation of internal signals of the model has been given in Fig. 18(c).
4. PV Array

In order to realize a PV array, four modules have been connected together in parallel as shown in Fig. 19 (a), and then the whole array was simulated. The results of current and power of array versus voltage are shown in Fig. 19 (b) and (c), respectively. An output power of about 160 W can be obtained from the array when the terminal voltage is about 17 volts.
5. Conclusion

A step by step mathematical modeling of solar energy conversion through photovoltaic effect was demonstrated using Matlab/Simulink. The model was simulated respect to the variation effects of voltage, insolation, temperature, series and parallel resistance. In this model, the simulation error due to an algebraic loop has been modified by insertion of delay block. The presented model can be considered as a basis model for PV systems/arrays in the framework of the Sim-Power-System Matlab/SIMULINK toolbox in the field of solar PV power conversion systems to predict the behavior of solar PV cells/module/ array under different circumstances.

References


