Physical Structure, Electrical Design, Mathematical Modeling and Simulation of Solar Cells and Modules

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Received: 16 December 2015; Accepted: 08 February 2016; Published: 30 March 2016

ABSTRACT In this study, the general physical structure, specifications and types of solar cells as well as their manufacturing processes, and mathematical model have been reviewed, in detail. This study is a complementary work to authors’ previous study which captured considerable interest in literature. Matlab/Simulink software based simulation of Photovoltaic (PV) model has been visually programmed; and current-voltage (I-V) and power-voltage (P-V) characteristics have been obtained for different number of series and parallel connected cells at different temperature values. The simulation results have been compared with theoretical results for the modeled solar cell. Results showed that the model established is quite well in agreement with the theoretical results and it is possible to apply the model to other hybrid systems. The model can also be used as a reference by solar cell manufacturers and in the experimental studies.

Keywords: Solar cell physical structure, electrical design, Solar cell types, Solar cell manufacturing process, Photovoltaic module modeling with Matlab/Simulink.

Cite this article: M.E. Şahin, H.I. Okumuş, Physical Structure, Electrical Design, Mathematical Modeling and Simulation of Solar Cell Modules, Turkish Journal of Electromechanics & Energy 1(1) 5-12 (2016)

1. INTRODUCTION
The continuous rise in energy demand has contribute to the increased research efforts in renewable energy area. Especially, the improvements in solar cells have elevated to the popularity of solar energy technologies. [1, 4]. Solar cells are Photovoltaic (PV) structures that they convert solar energy to electrical energy. Solar cells convert absorbed light energy to Direct Current (DC) electrical energy. Converters are used to convert DC current to suitable AC grid electricity. Photovoltaic modules have efficiencies between %5 to %20 depending on their types [5, 7].

The efficiency of solar cells is affected by the parameters such as internal resistance, contact structure, material used, variation of temperature and light density. Therefore, the effect of different parameters should be analyzed separately using a numerical model. As far as the authors’ knowledge there is no such detailed PV model in literature. Therefore, it was necessary to establish a new PV model that take necessary parameters into account [8-12]. The model to be developed will also be useful for PV manufacturers to test their products and for researchers in experimental studies [13-15]. In addition, it can also be used for compact systems simulation studies [16, 17].

If the literature on PV model design is reviewed, it was seen that only some of the parameters were used in PV modeling [6-11]. Some other studies defined the PV parameters based on experimental results and focused on specific matters in PV module design. There are application-based studies in literature, as well [12-15].

This work aimed for reviewing general physical structure, specifications and types solar cells as well as their, manufacturing processes, and mathematical models of solar cells, in detail. General mathematical model is given for solar cells including all the parameters which affect the efficiency calculation of PV systems. The PV model is programmed with Matlab/Simulink, and general I-V and P-V curves of solar cell were calculated for the different series and parallel connected cells at different temperature. The other details of these curves were given in previous
studies by the authors, and mostly focused on PV module simulations and their applications [15- 18].

2. PHYSICAL STRUCTURE AND TYPES OF SOLAR CELLS

2.1. The Working Principle of Solar Cells

Sun light fall on the solar cells and it is absorbed by photovoltaic cells. In the structure of solar cells, most of the electrons are included in n-type semiconductor material while most of the electrons hole included in p-type semiconductor material. Sun light breaks electron from the n-type semiconductor material. Energizing electrons flow of p-type to the n-type semiconductor material via an external circuit. This constant and unidirectional flow of electrons forms Direct Current (DC). Electrons flowing through the founded circuit which is used for the charging of batteries or different fields return to the p-type semiconductor material. In this way, electrical energy is obtained from solar cells. The study principle of solar cells is shown in Figure 1 [25].

2.2. Types of Solar Cells

Solar cells (Photovoltaics) are semiconductor materials that convert sunlight directly into electricity coming to the surface. 98% of the solar cell is Si (silicon); and silicon is an abundant material in the earth crust. Nonetheless, impure Si, has generally in silicon dioxide (SiO2, quartz) form and its purification is quite expensive. Therefore, the cost of solar panel increases.

Solar cells are generally classified as first, second and third generation. The crystalline silicon (c-Si and mc-Si) solar cells are accepted as first generation while thin film (a-Si, CdTe, CIS or CIGS) solar cells are regarded as second generation. Third generation solar cells are based on nanotechnology which are tandem, super tandem, intermediate band solar cells, etc.

The first generation (crystalline silicon) solar cells are divided into two types as Monocrystalline (c-Si, SiN) and Polycrystalline (mc-Si, poly-Si). Efficiency of monocrystalline solar cells is 15 to % 18. They are perfect for long time investments. 20% efficiency was reported in laboratory environment. The amortization period is noted between 4 to 6 years. The efficiency of this solar cell decreases to 7% after the 20 years. The pure crystal needed for these cells which make them very expensive. The cost of these type of cells is 4.5$/W, today [25]. The single monocrystalline solar cell is given in Figure 2(a).

The efficiency of polycrystalline solar cells is 12 to 15%. They do not have homogeneous crystal structures, hence they are cheaper. Maximum efficiency of 16.2% was achieved in laboratory environment for these cells. The amortization period is reported to be 2 to 5 years. The efficiency of this solar cell decreases to 14% after 20 years. The manufacturing price is cheaper than monocrystalline solar cells, and it is around 3.5$/W, currently. The single polycrystalline solar cell picture is shown in Figure 2(b).

Fig. 2. Different type of solar cells; (a) Monocrystalline, (b) Polycrystalline.

The second generation (thin film) solar cells are grouped into three species as Amorphous (a-Si), Cadmium Telluride (CdTe), and Copper Indium Gallium Selenium (CIGS). These types of cells have 7% of solar cell market share because of their low efficiency. These fairly thin structured cells, their thickness varies 1 to 4 µm only, have efficiency of 7 to 14%. The manufacturing price is as low as 1$/W [25, 32].

Amorphous (a-Si) solar cells’ efficiency is 8 to 10%, only. Nevertheless, its efficiency can be as high as 27% [33]. The payback time is in between 1.5 to 3.5 years. The efficiency lost of this type of solar cell is 21% during the years. The other drawback is that it needs very expensive tooling for its manufacturing.

Cadmium Telluride (CdTe) solar cells’ efficiency is around 17% for 1 cm2 and 11% for 8390 cm2 surface area [33]. Manufacturing price is considerably lower compared to other types of solar cells. Two photovoltaic panels made of CdTe were used by University of California at Riverside to produce hydrogen through electrolysis in 1992. This system is regarded as the first of its kind [34].

Copper Indium Gallium Selenium (CIGS) solar cells’ efficiency is 11 to 14% [33]. It is available with the glass or flexible substrates. It has a growing market share. There are large space requirement along with the expensive manufacturing process. The species of thin film solar cells are shown in Figure 3.

Fig. 3. Thin film Amorphous (a-Si) (a), Cadmium Telluride (CdTe) (b), Copper Indium Gallium Selenium (CIGS) (c), solar cells [26].

The third generation solar cells are nanotechnology (Tandem, Super Tandem, Intermediate Band etc.) based solar cells, and those are in R&D phase. As these types of cells will have the potential of higher efficiency, it makes them very
This technique is referred to as directional solidification. In contrast, using the Bridgeman method (b), the silicon can be cast in a separate crucible after the crystal is solidified and transmitted to the network. The main steps of manufacturing process are summarized in Figure 4 [26, 27].

Fig. 4. The main manufacturing steps of solar cells.

By melting the silicon quartz is obtained. The obtained product has 98% pure of silicon which also includes metals such as aluminium, iron [26]. This silicon is converted into polycrystalline structure with electronic rating called Siemens method and gains 99.99% purity. Silgrain material is used in this process. Silgrain is reacted with hydrochloric acid in the specific ratio of copper catalyst.

Ingots are the silicon casting and the Bridgeman method. The process is named after Polish scientist Jan Czochralski who invented the method in 1916 while investigating the crystallization rates of metals [28]. The polycrystalline ingot is melted in a vessel and is obtained by repeated freezing in another vessel. The manufacturing process is relatively easy, however; the efficiency is low. The most common methods for manufacturing multi-crystalline ingots are the silicon casting and the Bridgeman method. These two methods are shown in Figure 5. Silicon casting (Figure 5.a) can be carried out in a separate crucible after silicon is poured into it from a melting crucible, as indicated. In contrast, using the Bridgeman method (b), the silicon can be melted and directionally solidified in the same crucible. This technique is referred as directional solidification [29].

In the slicing stage the silicon is divided into thin slices called "wafers". Nevertheless, it is not enough a raw material to make solar cells. The multi-crystalline silicon ingot is cut by a wire saw into the blocks. These blocks are then cut by a wire saw into wafers. During this process the surface is repeatedly cleaned and is refined. The processing of square instead of circular solar cells into solar modules will increase the utilization of the available module area. Then, the resulting wafers have a thickness between 160 and 220 μm. The sawing of the ingot incurs an amount of 50 percent of material sacrifice. The slicing process is shown in Figure 6.

Plate area of mono or polycrystalline of solar cells is usually 125mm×125mm or 156mm×156mm and the thickness is in the range of 160-220 μm for the starting material. The next step is restoring the defects, cleaning the surface and phosphorus diffusion (POCL) process. While the front of the panel is selected generally as doped (adding impurities to) region by the minority carriers, back side of the panel is selected doped by the majority carriers. Phosphorus diffusion is used for n-type contact. Aluminum boron alloy is useful to increase the creation of very thin p-type contact and light absorption surface [24, 30]. The next stage is isolation of edges and addition of anti-reflection layer. In the process step of metallization, electric contacts are printed on the solar cell (both front and back side). This process is shown in Figure 7. After baking the electric contacts in an oven, the next step is the electrical power and optical quality is measured and the cells are classified accordingly.
Solar cell voltage is obtained by neglecting the series shunt resistor;

\[
V = \frac{n k T}{q} \ln \left( \frac{I_L + I_0 - I}{I_0} - R_s I \right)
\]  

Here, ideals factor \((n)\), series resistance \((R_s)\) and shunt resistor \((R_{sh})\) are the parameters which vary depending on the characteristics of the solar cell. Other parameters are; the Boltzmann constant \((k)\), the electron charge \((q)\) and the temperature of the solar cell \((T)\).

Equivalent circuit model of the solar cells was proposed in 1994 by Lorenzo [11]. This model consists of a current source and a diode connected in parallel. The series resistance \((R_s)\) represents the internal losses caused by the current flow of the solar cell. Connected parallel diodes resistance \((R_{sh})\) represents the leakage current taken place from the losses occurring in soil. It is often neglected as it is comparatively small with respect current produced. General equivalent circuit model of the solar cell is given in Figure 10.

The power given to the load, only depends on the resistance. If the \(R\) load is very small, solar cell works on M-N line as a current source near the short circuit current as illustrated in Figure 11. If the \(R\) load is very big, solar cell works on P-S curve as a voltage source near the open circuit voltage. The point A is the Maximum Power Point (MPP).

The other parameters affect the \(I-V\) curves are sunshine and temperature. The solar cell current is dependent on cellular operating temperature \((T)\) and the absorption of sunlight \((G)\) which is given in Equation 4. The amount of sunlight energy absorbed by the sun is \(G\), and intensity ranges from 0 to 1100 W/m\(^2\). The temperature coefficient, \(K_t\), is depended to the short-circuit current. Overall 3 mA/ºC constant value is received [9]. The effect of sunshine and temperature variations on \(I-V\) curves are shown in Figure 12. Depending on the light intensity, current \((I_{SC})\) and voltage \((V_{oc})\) increases or decreases, however, temperature increase reduces the voltage \((V_{oc})\) while the current \((I_{SC})\) slightly increases.

4. ELECTRICAL SPECIFICATIONS OF SOLAR CELLS

Solar cells are based on the Shockley diode equation in Equation 1, electrically. However, with the other general solar cell parameters the equality is given as an Equation 2.

\[
I = I_0 \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right]
\]

\[
I = I_L - I_0 \left[ \exp \left( \frac{q(V + R_s I)}{n k T} \right) - 1 \right] \frac{V + R_s I}{R_{sh}}
\]  

In addition, a PV-system consists of multiple components, including cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output. The electrical specifications of solar cells and PV module design using mathematical equations will be viewed in the next step.
\[ I_L = \left[ I_o + K_i (T - T_{ref}) \right] G \quad (4) \]

Voltage equation can be derived from the PV module current equation and solar cells current Equation 4 which depends on \( T \) and \( G \), embedded in it. Final form of the equation can be written as in Equation 6. The details of these equations are given in previous studies [18, 23].

\[ V_{pv} = \frac{N_p n k T}{q} \ln \left[ \frac{I_{sc} + K_i (T - T_{ref}) G + I_L - I_{pv} + N_p}{I_o N_p} \right] - \frac{N_p}{N_p} R_s I_{pv} \quad (6) \]

Using Equation 6, the solar cells module is programmed visually with the Matlab/Simulink software as it can be seen in Figure 15.

![Figure 15](image_url)

Using the equivalent model of solar cells module in Figure 14, the simulations were performed. Constant and variable parameters used in these simulations are given in Table 1. This model needs some more electrical components to be used as an electrical source for circuit’s simulations [18, 23].

<table>
<thead>
<tr>
<th>Table 1. Constant and variable parameters used in the simulations.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant Accepted Parameters</strong></td>
</tr>
<tr>
<td>Boltzmann constant ((k))</td>
</tr>
<tr>
<td>Electron charge ((q))</td>
</tr>
<tr>
<td>Reference temperature ((T))</td>
</tr>
<tr>
<td>Short circuit current temperature constant ((K_i))</td>
</tr>
<tr>
<td>Diode current ((I_o))</td>
</tr>
<tr>
<td>Short circuit current ((I_{sc}))</td>
</tr>
<tr>
<td><strong>Variable Accepted Parameters</strong></td>
</tr>
<tr>
<td>The number of series cells ((N_s))</td>
</tr>
<tr>
<td>The number of parallel cells ((N_p))</td>
</tr>
<tr>
<td>Series internal resistance ((R_s))</td>
</tr>
<tr>
<td>Variable temperature ((T_{inc}))</td>
</tr>
<tr>
<td>The light absorption ((S_i=\gamma))</td>
</tr>
<tr>
<td>Ideality factor ((\alpha=\gamma))</td>
</tr>
</tbody>
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6. SIMULATION RESULTS FOR SOLAR CELL MODULE

The solar cell modules current-voltage (I-V) and power-voltage (P-V) characteristics were obtained as in Figure 16 using the simulations of solar cell modules and the parameters given in Table 1. The maximum power point is around 1800 Watts for 17V.
Fig. 16. The solar cell modules (a) current-voltage (I-V) and (b) power-voltage (P-V) characteristics.

Figure 17 (a) and (b) show how the solar cells module current-voltage (I-V) characteristics vary for different number of cells connected in serial and parallel. As the number of serial connected solar cell increases, the open circuit voltage increases and the short circuit current remains same. Likewise, as the number of parallel connected solar cell increases, the short circuit current increases and open circuit voltage remains same.

Fig. 17. Current-voltage variation characteristics of for different cell numbers of solar modules connected in (a), series and (b) parallel.

Figure 18.a and b show (I-V) and (P-V) curves at different temperatures for the solar cell. In Figure 18 (a), open circuit voltage of the solar cell temperature is decreased ($V_{oc}$), but short circuit current value ($I_{sc}$) is increased in a small amount. However, as shown in Figure 18 (b), the maximum power point decreases with temperature increase. From 0 °C to 100 °C maximum power point changes from 2600 W to 1800 W, approximately. This shows the efficiency decreases in solar cells depending on temperature. This is in well agreement with the theoretical calculations.

Fig. 18. a) Current-Voltage (I-V), b) Power-Voltage (P, V) for different temperature values (from $T = 0$ °C to $T = 100$ °C).
These results show only the variation of (I-V) and (P-V) curves for different numbers of serial and parallel connected cells with respect to temperature. Effect of other parameters was examined in a detail by the authors in a previous study [18].

7. CONCLUSION

General structure, specifications types as well as manufacturing processes and mathematical model of solar cells have been reviewed, in detail in this study, the solar cell of the resulting mathematical model is visually programmed with the Matlab/Simulink software and the solar cell module was simulated. The obtained simulation results were found to be quite well agreement with ideal PV sources known in theory. It is noted that the modeled solar cells can be used in combination with other electrical systems.

Acknowledgement

This study was supported through The Scientific & Technological Research Council of Turkey (TUBITAK) project # 111E292.

References


Biographies

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