Review Article | Submit Manuscript

Turkish Journal of Electromechanics & Energy

ISSN: 2547-975X

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

M. E. Şahin[1*], H. İ. Okumuş[2]

[1]Department of Electrical and Electronics Engineering, Recep Tayyip Erdoğan University 53100, Rize, TURKEY
[2]Department of Electrical and Electronics Engineering, Karadeniz Technical University, 61080, Trabzon, TURKEY

Received: 16 December 2015; Accepted: 08 February 2016; Published: 30 March 2016
Academic Editor: Ö. N. Cora
Turk J Electrom Energ Vol.: 1 No: 1 Page: 5-12 (2016)
SLOI: http://www.sloi.org/
*Correspondence E-mail: mustafaerginsahin@yahoo.com

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.İ. 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 reneawable 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].

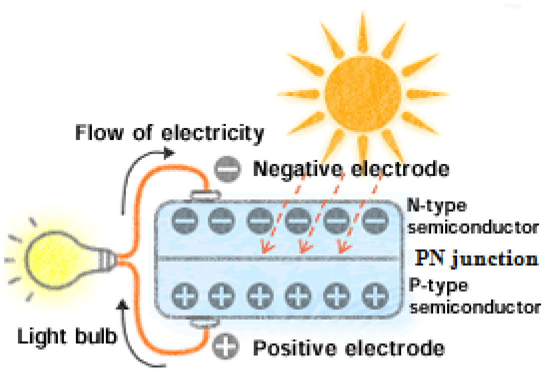


Fig. 1. The working principle of solar cells [25].

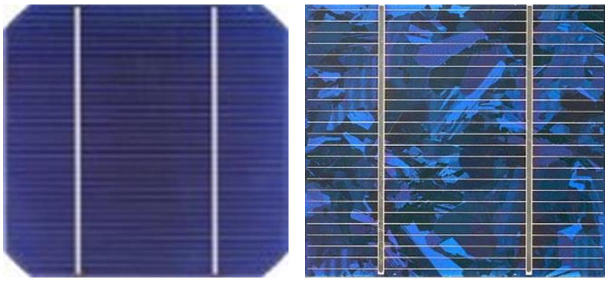
2.2. Types of Solar Cells

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 (SiO_2, 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).



(a) (b)

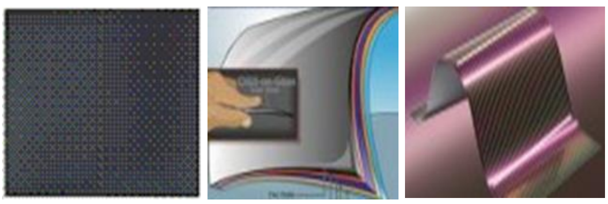
Fig. 2. Different type of solar cells; (a) Monocrystalline, (b) Polycrystalline.

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 thicknesses vary 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 cm^2 and 11% for 8390 cm^2 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 of 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.



(a) (b) (c)

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 attractive and there is regarded as major breakthrough if they can be manufactured cost-effectively. Projected cost is 0.4 $ / kW [33].

For Super Tandem cells, the efficiency is 86.8% in theory and experimental efficiency of 35.4% is achieved for 1 cm^2 in literature [27, 33]. The efficiency is 63.2% for intermediate band cells in theory but experimentally is not achieved yet. Manufacturing oriented problems have not been solved yet for hot carrier cells. When those are solved, it is expected to have efficiency as high as Super Tandems.

3. MANUFACTURING PROCESS OF SOLAR CELLS

Solar cells are manufactured from ingots having silicon crystal with 99% purity after processing the sea sand. Then the material is made suitable for electrical conduction with a metal coating, via scribing and slicing into thin plates. The obtained solar cells are then formed and modules are manufactured. These modules form a photovoltaic system and those are combined with required converters 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 aluminum, 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.

Ingot is the name given to the semiconductor material in solid state. It can be in mono or polycrystalline form. A mono crystal ingot is obtained by pulling the crystal from the silicon melt. 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].

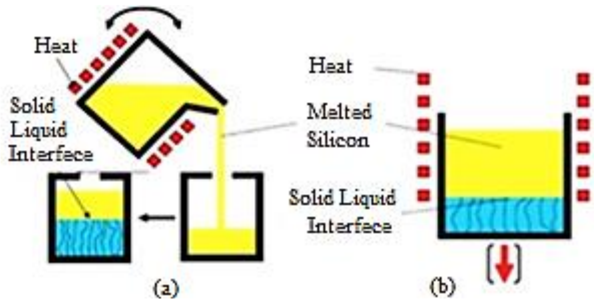


Fig. 5. Silicon casting (a), Bridgeman methods (b) for manufacturing multi- crystalline ingots.

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.

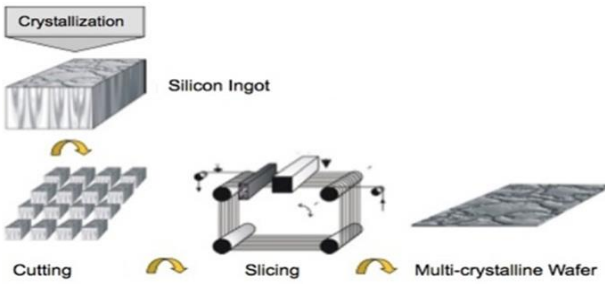


Fig. 6. The slicing process of the ingots [24].

Plate area of mono or polycrystalline of solar cells is usually125mm×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.

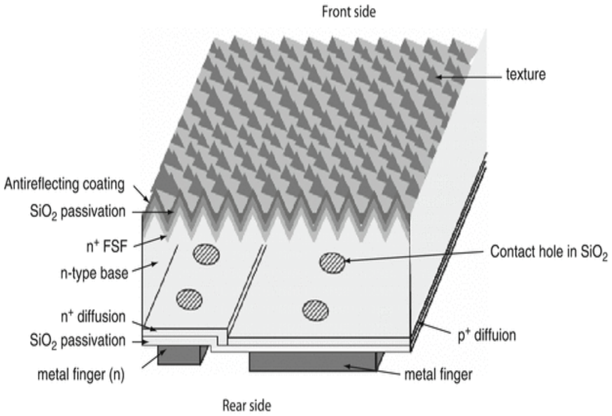


Fig. 7. Diffusion and metallization process made of cell section [30].

In order to obtain the appropriate voltages and outputs for different applications, single solar cells are interconnected to form larger units. Cells connected in series have a higher voltage, while those connected in parallel produce more electric current. Cells connection is shown in Figure 8.


Fig. 8. Photovoltaic cells module connection.

The interconnected solar cells are usually embedded in transparent Ethyl-Vinyl-Acetate, fitted with an aluminum or stainless steel frame and covered with transparent glass on the front side. This process is called lamination process. The lamination process of PV panel is shown in Figure 9.

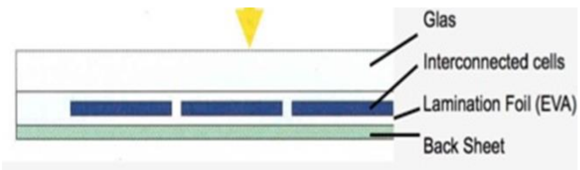


Fig. 9. The lamination process of photovoltaic panels.

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.

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.

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

$$I = I_L - I_0\left[\exp\left(\frac{q(V+R_s.I)}{n.k.T}\right)-1\right]-\frac{V+R_s.I}{R_{sh}} \tag{2}$$

Solar cell voltage is obtained by neglecting the series shunt resistor;

$$V = \frac{n.k.T}{q}\ln\left[\frac{I_L+I_0-I}{I_0}\right]-R_s.I \tag{3}$$

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.

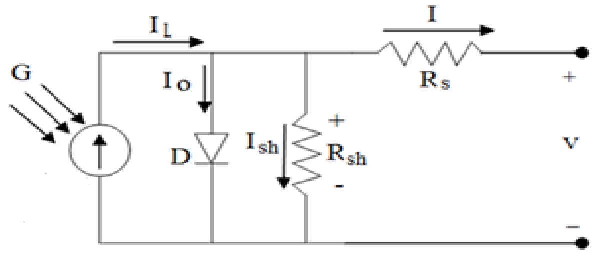


Fig. 10. General equivalent circuit model of the solar cell.

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).

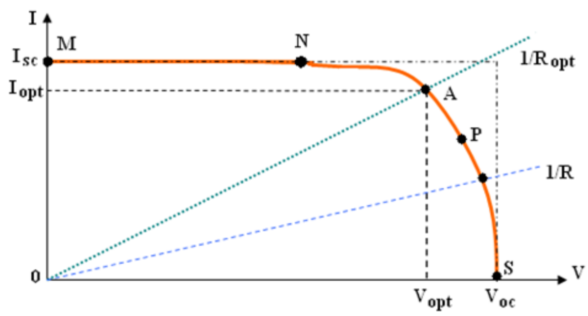


Fig. 11. Current-Voltage *(I-V)* characteristic of solar cell.

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_i, 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.

$$I_L = \left[I_{sc} + K_I(T - T_{ref})\right].G \qquad (4)$$

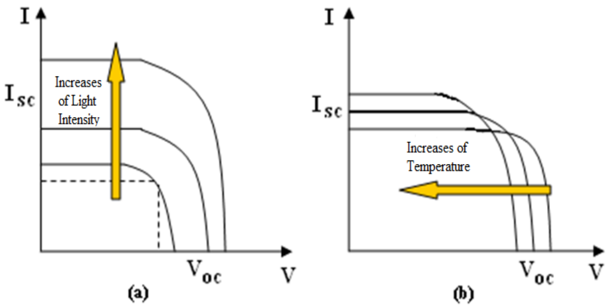
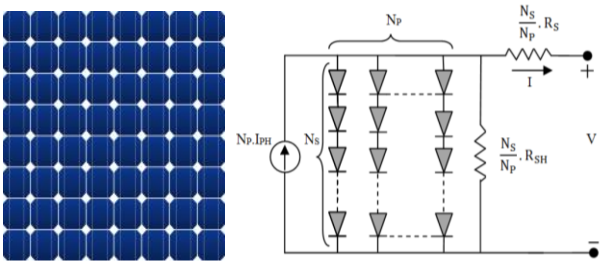


Fig. 12. Sunshine (a) and temperature (b) variations how to effect *I-V* curves.

5. EQUIVALENT CIRCUIT OF SOLAR CELL MODULE AND MODELING

A simple solar cell can have a maximum of 0.5 V at 2 W powers. Thus, the desired voltage and current can be obtained by connecting the cells either in series and parallel. The resulting structures are referred as solar cell modules. The number of series cells is taken as N_S and parallel cells are taken as N_p in equivalent circuit model. The PV module structure and equivalent circuit model is shown in Figure 13 (a) and (b).



(a) (b)

Fig. 13. (a) PV module structure, (b) Equivalent circuit model.

Increasing the number of serial cells increases voltage and increasing the number of parallel cells increases current as a characteristic of solar module. This situation is shown in *I-V* curves given in Figure 14. The general current of the PV module in which serial resistance (R_S) is neglected, is shown in Equation 5.

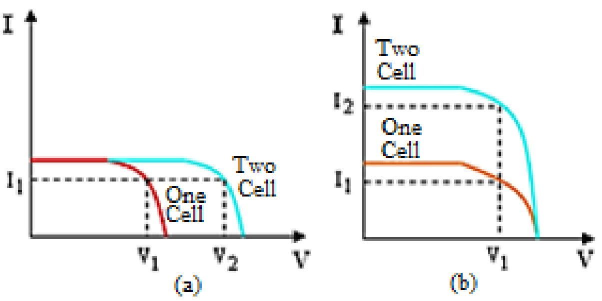


Fig. 14. *I-V* curves for series (a), parallel (b) connected cells.

$$I = N_P.I_{PH} - N_P.I_0\left[\exp(q.\left(\frac{V}{N_S}+\frac{I.R_S}{N_P}\right)/k.T_C.A) - 1\right] \qquad (5)$$

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].

$$V_{PV} = \frac{N_S.n.k.T}{q}\ln\left[\frac{(I_{SC}+K_I(T-T_{ref})).G + I_0 - I_{PV} + N_P}{I_0.N_P}\right] - \frac{N_S}{N_P}.R_s.I_{PV} \qquad (6)$$

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

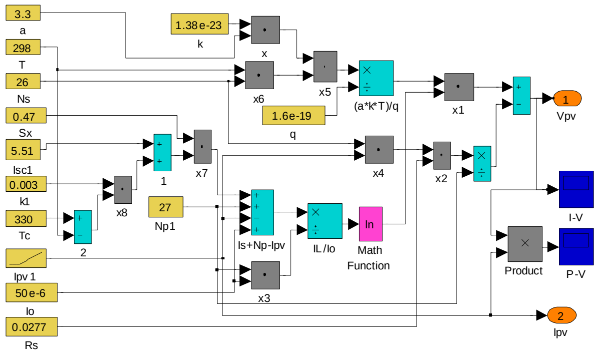


Fig.15. Matlab/Simulink equivalent model of the solar cells module.

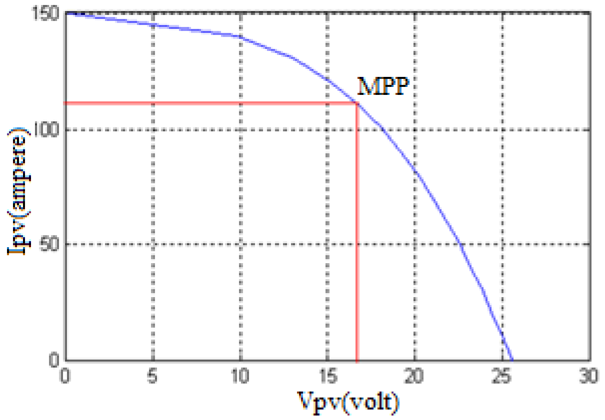
Using the equivalent model of solar cells module in Figure 14, the simulations were performed. Constant and variable parameters used in these simulations are given in Table 1. This model needs some more electrical components to be used as an electrical source for circuit's simulations [18, 23].

Table 1. Constant and variable parameters used in the simulations.

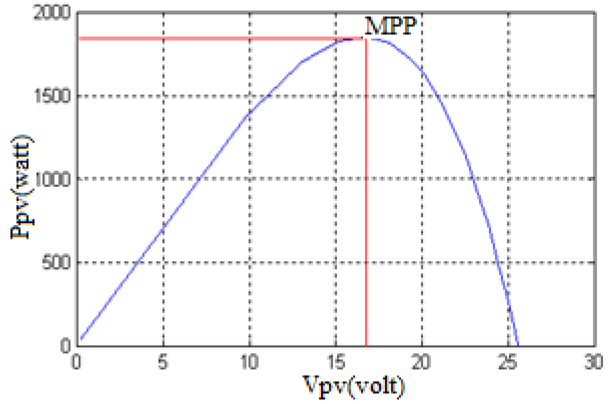
Constant Accepted Parameters	Values
Boltzmann constant (*k*)	1.38x10-23J/K
Electron charge (*q*)	1.6x10-19 C
Reference temperature (*T*)	(273+25) K
Short circuit current temperature constant (K_I)	3mA/ºC
Diode current (I_o)	50µA
Short circuit current (I_{sc})	3.92A
Variable Accepted Parameters	**Values**
The number of series cells (N_s)	105
The number of parallel cells (N_p)	148
Series internal resistance (R_s)	0.0277Ω
Variable temperature (T_x)	0-100ºC
The light absorption (S_x=*G*)	0.1-1kW/m²
Ideality factor (*a*=*n*)	1.2-5

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.



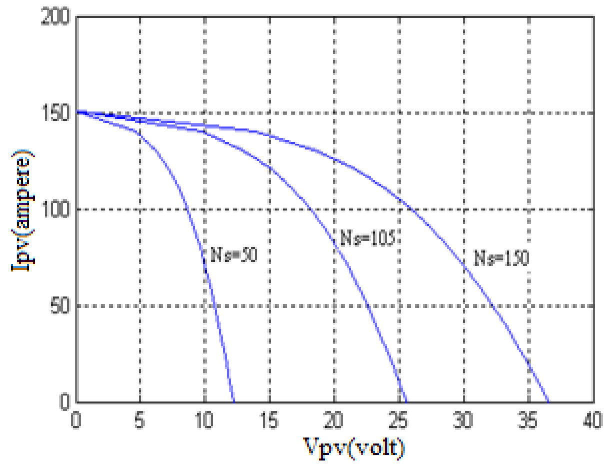
(a)



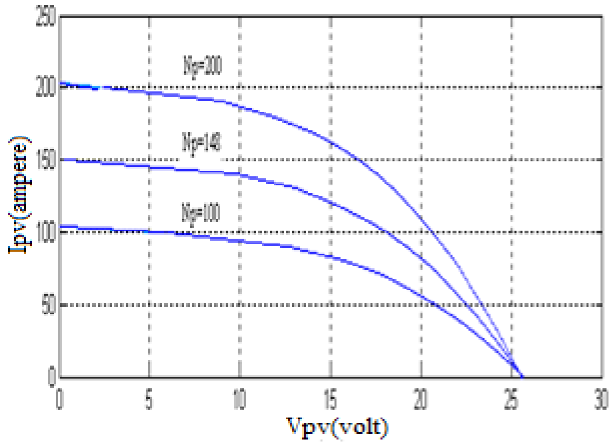
(b)

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.



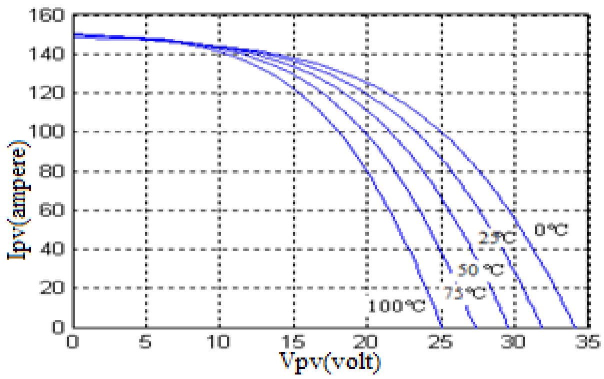
(a)



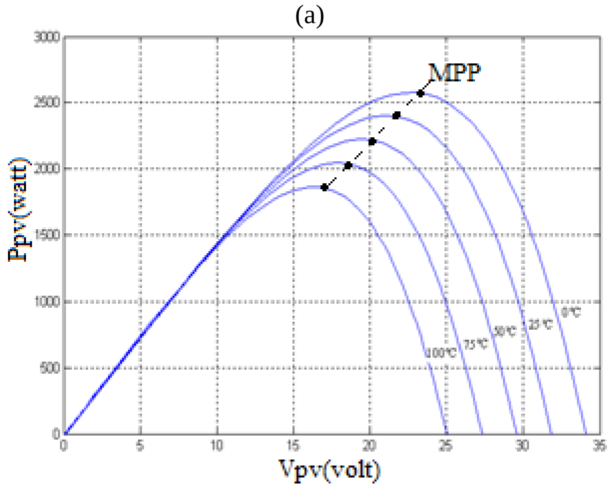
(b)

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.



(a)



(b)

Fig. 18. a) Current-Voltage (I-V), b) Power-Voltage (P, V) for different temperature values (from T = 0 ° 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

[1] A. Joyce., C. Rodrigues, R. Manso, Modeling a PV System, Renewable Energy 22, 275-280 (2001).
[2] L. Fangrui, D. Shanxu, L. Fei, L. Bangyin, and K. Yong, A Variable Step Size INC MPPT Method for PV Systems, IEEE Transactions on Industrial Electronics, 55(7), (2008).
[3] M.A.S. Masoum, H. Dehbonei, E.F. Fuchs, Theoretical and Experimental Analyses of Photovoltaic Systems with Voltage and Current-Based Maximum Power-Point Tracking, IEEE Transactions on Energy Conversion, 17(4), (2002).
[4] A.D. Hansen, P. Sørenson, L.H. Hansen, H. Bindner, Models for a Stand-Alone PV System, Risø National Laboratory, Roskilde, Report, December, (2000).
[5] M. Uzunoglu, O.C. Onar, M.S. Alam, Modeling, Control and Simulation of a PV/FC/UC Based Hybrid Power Generation System for Stand-alone Applications, Renewable Energy 34, 509-520, (2009).
[6] G.R. Walker., P.C. Sernia., Cascaded DC-DC Converter Connection of Photovoltaic Modules, IEEE Transactions on Power Electronics, 19(4), 1130-1140, July (2004).
[7] G. Walker, Evaluating MPPT Converter Topologies Using A Matlab PV Model, Journal of Electrical & Electronics Engineering, 21(1), 49-56,(2001).
[8] I.H. Altaş, A.M. Sharaf, A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment, IEEE Conference, 341-345, (2007).
[9] H.L. Tsai., C.S. Tu., and Y.J. Su, Development of Generalized Photovoltaic Model Using Matlab/Simulink, WCECS 2008, San Francisco, USA, October 22-24, (2008).
[10]M.G.L. Francisco, Model of Photovoltaic Module in MATLAB, II CIBELEC Conference, (2005).
[11] E. Lorenzo, Solar Electricity Engineering of Photovoltaic Systems, Artes Graficas Gala, S.L., Spain, (1994).
[12] M.E. Ropp, S. Gonzales, Development of Matlab/Simulink Model of a Single- Phase Grid-Connected Photovoltaic System, IEEE Transactions on Energy Conversion, (2009).
[13] H. Patel, V. Agarwal, MATLAB-Based Modeling to Study the Effects of Partial Shadings on PV Array Characteristics, IEEE Transactions on Energy Conversion, 23(1), 302-311, March (2008).
[14] A.A. Hegazy, Comparative Study of the Performances of Four Photovoltaic/Thermal Solar Air Collectors, Energy Conversion& Management 41, 861-881, (2000).
[15] T.S. Navruz, M. Sarıtaş, Efficiency Variation of The Intermediate Band Solar Cell Due to The Overlap Between Absorption Coefficients, Solar Energy Materials & Solar Cells 92, 273-282, (2008).
[16] M.E. Sahin, H.İ. Okumus, A Fuzzy Logic Controlled PV-Powered Buck–Boost DC-DC Converter for Battery-Load System, In the Proceedings of INISTA International Conference, July 2-4th, Trabzon, TURKEY, 325-349, (2012).
[17] A.M. Sharaf, M.E. Sahin, A Novel Photovoltaic PV-Powered Battery Charging Scheme for Electric Vehicles, ICEAS IEEE Conference, India, (2011).
[18] M.E. Şahin, H.İ. Okumuş, Modelling and Simulation of Solar Cell Module in Matlab/Simulink, The Journal of Electrical, Electronics, Computer and Biomedical Engineering 3(5), 17-25, (2013).
[19] K. Bücher, G. Kleiss, D. Bätzner, Photovoltaic Modules in Buildings: Performance and Safety, Renewable Energy 15, 545-551, (1998).
[20] A. Manallah, M. Bouafia, A. Guechi, Photometric Study of a Solar Cell Panel Si-c, NuRER Conference, İstanbul, (2012).
[21] National Aeronautics and Space Administration, Science Mission Directorate, Visible Light. Retrieved February 06, 2016, from Mission: Science website: http://missionscience.nasa.gov/ems/09_visiblelight.html, (2010).
[22] A.S. Joshi, I, Dinçer, B.V. Reddy, Performance Analyses of Photovoltaic Systems: A Review, Renewable and Sustainable Energy Reviews 13, 1884–1897, (2009).
[23] M.E. Şahin, 'Design and Control of Parallel Connected Buck-Boost Converter for Hybrid Energy System, Ph.D. Dissertation, Karadeniz Technical University, Turkey, (2014).
[24] J. Ventre, Photovoltaic Systems Engineering, Taylor & Francis, Second Edition, (2004).
[25] Converting Sunlight into Electricity, Kyocera Corporation, retrieved from Kyocera website: http://global.kyocera.com/solarexpo/solar_power/mechanism.html, Last Access Date: February 06th, 2016.
[26] M. Augustin, L. Castaner and T. Markvart. Solar cells: materials, manufacture and operation, Academic Press, (2012).
[27] S. Tatsuo, Advances in crystalline silicon solar cell technology for industrial mass production, NPG Asia Materials 2.3, 96-102, (2010).
[28] J. Czochralski, A new method for the measurement of the crystallization rate of metals, Zeitschrift für Physikalische Chemie, 92, 219–221, (1918).
[29] P. W. Bridgman, Certain Physical Properties of Single Crystals of Tungsten, Antimony, Bismuth, Tellurium, Cadmium, Zinc, and Tin scheme, Proceedings of the American Academy of Arts and Sciences, 60(6), 305–383, (1925).
[30] S. Martinuzzi, and at all., Silicon Solar Cells, Crystalline, Encyclopedia of Sustainability Science and Technology, Springer New York, 9196-9240, (2012).
[31] M. Roger, and A. Abtahi, Photovoltaic systems engineering. CRC press, (2010).

[32] M. Keiichiro, et al., Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell, Photovoltaics, IEEE Journal of 4.6, 1433-1435, (2014).
[33] M.A. Green, et al., Solar cell efficiency tables (Version 45), Progress in photovoltaics: research and applications 23.1, 1-9, (2015).
[34] D.L. Block, Production of hydrogen by photovoltaic-powered electrolysis. Task 1 report. No. DOE/AL/85802--T2-Pt. 1; FSEC-CR--857-95-Pt. 1. Florida Solar Energy Center, Cocoa, FL (United States), (1995).

Biographies

Mustafa Ergin Şahin was born in, 1978 in Trabzon, Turkey. He received his B.Sc. degree in Electrical & Electronics Engineering from Karadeniz Technical University (KTU), M.Sc. degrees from Gazi University (GU) in Ankara and Ph.D. degrees in KTU, Trabzon, Turkey, in 2002 and 2006, 2014, respectively. He is currently an Assistant Professor in Electrical and Electronics Engineering Department at RTE University. He was worked at different projects on low voltage power systems and relay manufacturer for power systems. He is an active reviewer to the scientific journals in the field. He has been a member of the Chamber of Electrical Engineers in Turkey. His main research interests are power electronics and utilization of renewable energy.
E-mail: mustafaerginsahin@yahoo.com

Halil İbrahim Okumuş was born in 1963, in Rize, Turkey. He received his B.Sc. degree in Electrical & Electronics Engineering from Karadeniz Technical University (KTU) and Ph.D. from Bristol University (UB), United Kingdom, in 1992 and 2001, respectively. He is currently Associate Professor in Electrical and Electronics Engineering Department at KTU. He is a senior Member of IEEE Power Electronics Society. He has been a member of the Chamber of Electrical Engineers in Turkey. His main research area is intelligent control of power systems and utilization of renewable energy.
E-mail: okumus@ktu.edu.tr