INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
Rustu Eke et al., Vol.2, No.4, 2012

Seasonal Variation of Internal Parameters of an Amorphous Silicon (a-Si) Thin Film Photovoltaic Module

Rustu Eke*

Rustu Eke*,**‡, Sener Oktik***

* Mugla Sıtkı Kocman University, Clean Energy Research & Development Centre, Mugla,Turkey

** Mugla Sıtkı Kocman University, Faculty of Sciences, Department of Physics, Photovoltaic Material and Device Laboratory, Mugla,Turkey

*** Turkiye Sise ve Cam Fabrikalari A.S.Is Kuleleri, Kule-3 34330 4.Levent Istanbul Turkiye

erustu@gmail.com, seneroktik@gmail.com

‡ Corresponding Author; Rustu Eke, Mugla Sıtkı Kocman University, Faculty of Sciences, Department of Physics, Photovoltaic Material and Device Laboratory, 48120 Mugla,Turkey, +90 252 211 1601, Fax: +90 252 2111472, erustu@gmail.com

Received: 21.06.2012 Accepted: 05.08.2012

Abstract- Operating parameters of a KA58 Amorphous Silicon (a-Si) photovoltaic module is investigated as a function of solar irradiation and atmospheric conditions using current-voltage curves taken for a year from April to May at Mugla Sıtkı Kocman University PV Outdoor Test Site. Single diode model is proposed to explain the current-voltage curves of thin film solar cells and modules. It is observed that the operating parameters of a KA58 a-Si photovoltaic module exhibit significantly different response to the changes in solar radiation and weather conditions in a period of 12 months. Correlations between internal parameters, namely R_S, R_P, I_L, I_O and a (modified ideality factor) of module and solar irradiation and atmospheric data is investigated.

Keywords- Outdoor measurements of solar cells and modules; amorphous silicon module performance, series resistance, parallel resistance, single diode model.

1. Introduction

Photovoltaic (PV) systems offer an environmentally friendly way to meet growing electricity demand. The cumulative installed capacity of all PV systems around the world at the end of 2009 grew to 22,878 MWp. The cumulative capacity was 480MWp in 1995, 1428MWp at 2000 and 6956MWp at the end of 2006 [1,2].Cumulative installations of PV cells and modules around the world have been growing at an average annual rate of more than 30% since 1995 and it is raised by 45% up to 22,9GWp in 2009 . For the solar production industry, global annual installation of PV modules is projected to rise from 22.9 GWp in 2009 to more than 179 GWp in 2030 [2].

Silicon is the basic material required for the production of solar cells based on crystalline technology. 93% of the world market is based on crystalline silicon and the share of thin film technology based solar cells is round 6% at the end of 2006. It is expected to gain a much larger share of the PV market in the future. EPIA expects a growth in the thin film market share to reach about 20% of the total production of PV modules by 2010 and 40% by 2030 [1,2].

Thin film modules are constructed by depositing extremely thin layers of photosensitive materials onto a low-cost backing such as glass, stainless steel or plastic. These results in lower production costs compared to the more material-intensive crystalline technology, a price advantage which is currently counterbalanced by substantially lower efficiency rates. Three types of thin film modules are commercially available at the moment. These are manufactured from amorphous silicon (a-Si), copper indium diselenide (CIS, CIGS) and cadmium telluride (CdTe).

Among the three commercially available thin film technologies, a-Si is the most important in terms of production and installation. Some analytical and numerical methods are developed for the characteristics of solar cells [3,4].

The performance parameters of PV modules are optimized at some reference condition, usually at standard test conditions (STC) of 1000 W/m^2 of irradiance, 25 °C cell temperature and air mass 1.5 global spectrums. And internal parameters of PV modules are always given at these conditions by manufacturers. However, these conditions rarely occur outdoor and thus variations of electrical parameters of PV devices need to be investigated and modeled. There are a few models, both in numerical and analytical, in the literature for simulating the behavior of PV devices for specific irradiance and temperature conditions [5,6].

The purpose of this study is to evaluate the effect of seasonal changes in the operating parameters of a KA58 Amorphous Silicon (a-Si) thin film module as a function of solar irradiation and atmospheric conditions.

2. PV Model and Methodology

The electrical power available from a PV cell/module can be modeled with the circuit shown in Fig. 1 [6]. Single diode (single exponential) model is considered as the equivalent PV model. Five parameters must be known in order to determine the current and voltage, and thus the power delivered to the load. These parameters are I_L, the light generated current or photovoltaic current, I_O , dark saturation current, R_S , series resistance, R_{SH} or R_P , shunt or parallel resistance and , is a coefficient called as modified ideality factor. Herein, the modified ideality factor is calculated as $a = N_{CS} n k_B T_C / q$; herein, N_{CS} represents number of the solar cells or PV modules, n represents diode ideality or quality factor, k_B represents Boltzmann constant, q represents electron charge and T_C represents temperature of the solar cell or PV module in Kelvin [6].

The following Equation may be written for the current flowing through the circuit at any chosen point according to current rule of Kirchoff. Wherein, I_L represents the light generated current by in the solar cell or a PV module, I_D represents diode current and I_{SH} represents leakage currents.

$$I = I_L - I_D - I_{SH} \tag{1}$$

When I_{SH} and I_D is inserted in Eq.1 the current-voltage relationship at a fixed cell/module temperature and irradiation for the circuit will be expressed as:

$$I = I_L - I_O\left\{\exp\left[\frac{(V+IR_S)}{a}\right]-1\right\}-\frac{V+IR_S}{R_{SH}} \tag{2}$$

Where V is the voltage across the load. Dark saturation current (I_O) depends on band gap and temperature of the material used in manufacturing the solar cell [7].

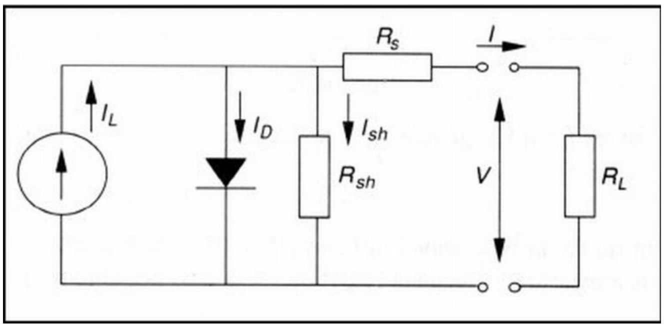

Fig. 1. Equivalent circuit of a solar cell or a PV module.

Series resistance (R_S) and shunt or parallel resistance (R_{SH}) can be determined by defining R_{SO} around open circuit voltage and R_{SHO} around short circuit current with the help of gradients of the current-voltage curve around open circuit voltage and short circuit current.

$$R_{SO} = -\left(\frac{dV}{dI}\right)_{V=V_{OC}} \tag{3}$$

$$R_{SHO} = -\left(\frac{dV}{dI}\right)_{I=I_{SC}} \tag{4}$$

A set of equations is obtained by arranging Eq.2, which is given for the current, around open circuit voltage, short circuit current and the maximum power point at which maximum power is obtained from the device to determine five important parameters for the solar cell or PV module. Certain assumptions are required to be made to solve the five parameters analytically from the obtained Equation set [8,9]. Because $\exp\left(\frac{V_{OC}}{a}\right) >> \exp\left(\frac{I_{SC}R_S}{a}\right)$ and $R_S << R_{SH}$ in the obtained equations, then $1+\frac{R_S}{R_{SH}} \approx 1$. Thus, such parameters of a solar cell or a PV module, R_S, I_L, I_O and a may be calculated as seen below:

$$R_S = \frac{R_{SO}\left(\frac{V_{OC}}{a}-1\right)+R_{SHO}\left(1-\frac{I_{SC}R_{SO}}{a}\right)}{\frac{V_{OC}-I_{SC}R_{SHO}}{a}} \tag{5}$$

$$I_L = I_O\left[\exp\left(\frac{V_{OC}}{a}\right)-1\right]+\frac{V_{OC}}{R_{SH}} \tag{6}$$

$$I_O = \frac{I_{SC}\left(1+\frac{R_S}{R_{SH}}\right)-\frac{V_{OC}}{R_{SH}}}{\exp\left(\frac{V_{OC}}{a}\right)} \tag{7}$$

$$a = \frac{V_{MPP} + I_{MPP}R_S - V_{OC}}{\ln\left\{\dfrac{\left(I_{SC} - I_{MPP}\right)\left(1 + \dfrac{R_S}{R_{SH}}\right) - \dfrac{V_{MPP}}{R_{SH}}}{I_{SC}\left(1 + \dfrac{R_S}{R_{SH}}\right) - \dfrac{V_{OC}}{R_{SH}}}\right\}} \qquad (8)$$

If parallel resistance is

$$R_{SH} = R_{SHO} - R_S \qquad (9)$$

Then, the five important parameters for a solar cell and PV module can be calculated by using a single current-voltage curve. A value is assigned for series resistance (R_S) as initial value. After parallel resistance value (R_{SH}) and modified ideality factor (a) given by Equation (8) are calculated, current generated by light (I_L) is calculated by using the Eq.6 and RS , which is expressed by Eq.5 is re-calculated. The new calculated value of RS is used in Eq.7 to find the dark saturation current (I_O). Thus, all required parameters for a solar cell or PV module are determined.

2.1. Measurement System

A multi-channel measurement system in Mugla Sıtkı Kocman University Clean Energy Resources Research and Development Center (MUTEK R&D) developed by Aescusoft can scan the whole current-voltage curve of a solar cell or photovoltaic module in 20 seconds [10]. Voltage of solar cell or PV module under test is scanned at 80 points from the value around short circuit current (0V) to the open circuit voltage (V_{OC}) and current value corresponding to each voltage value is measured and saved in a file. These measurements are performed in a 2 minute period and made available during a day. Variations in the internal parameters of the solar cell or PV module can be observed within a day or between seasons by using the obtained current-voltage curves. Fig.2 shows the connection box of the multi-channel measurement system. 4 points measurement method is used (2 cables for load and 2 cables for sense) for the current and voltage measurements of the tested PV modules.

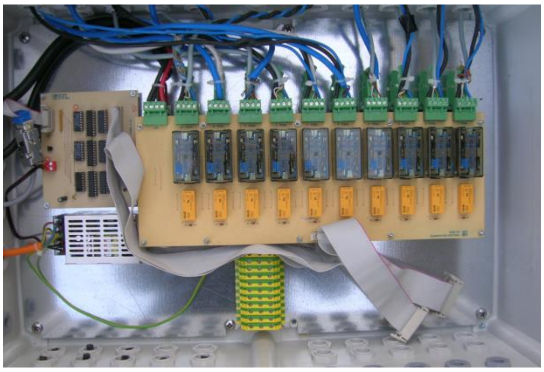

Fig. 2. Connection box of the multi-channel measurement system.

Parameters of solar cell and PV module vary under operating conditions and lower performances are obtained compared those given under STC. These conditions combine solar irradiation on a clear summer day, temperature of solar cell or photovoltaic module on a clear winter day and solar spectrum on a clear spring day. However, these conditions are encountered rarely. High irradiation levels occur on surfaces of PV modules exceeding 1000 W/m^2 in summer months; however, because ambient temperature is high, operating temperatures of PV modules may reach up to 60-70 ºC. In winters, although ambient temperature and the consequent operating temperature of PV modules are lower (it is close to 35 ^{0}C at noon time), solar irradiation, which can be obtained on surfaces of PV modules, is below 1000 W/m^2.

2.2. KA58 Amorphous Silicon (a-Si) Photovoltaic Module

Electrical power conversion efficiency of the KA58 Amorphous Silicon (a-Si) Photovoltaic Module, whose performance has been observed since April in Mugla Sıtkı Kocman University's photovoltaic test area, is defined as 6.62% under STC. The manufacturer's electrical values for the KA58 a-Si photovoltaic module with power of 58W under STC are given in Table 1.

The tested PV module consisting of 100 series-connected a-Si solar cells covers an area of 0.876m^2. According to the data provided by the manufacturer, the potential power, which can be generated at the maximum power point, decreases by 0.34 - 0.49% for an increase of 1°C in temperature depending on operating conditions. Ideality factor of the KA58 a-Si photovoltaic module under STC is given as 2.21. Table 1 shows values of some physical parameters and coefficients for variation of current and voltage depending on temperature.

Table 1. Parameters of KA58 Amorphous Silicon (a-Si) Photovoltaic Module under STC

I_{SC} (A)	V_{OC} (V)	I_{MPP} (A)	V_{MPP} (V)	R_S (Ω)	R_{SH} (Ω)	$I_{0,ref}$ (nA)	µV$_{OC}$ (mV/ºC)	µI$_{SC}$ (mA/ºC)
1.10	85.0	0.92	63.0	8.39	1050	229	-331	0.8

3. Results and Discussion

For establish the current-voltage curve of the photovoltaic module, 80 voltages and the corresponding currents values taken with the help of electronic load in 10-20 s were measured. Short circuit current (I_{SC}), open circuit voltage (V_{OC}), the current at the maximum power point (I_{MPP}) and the voltage at the maximum power point (V_{MPP}) were determined for the PV module under test. New current values corresponding to the measured voltage values were calculated by using Blas Model based on single diode model. Although small variation exist between the values calculated by using Phang model and empirical values obtained for the KA58 a-Si PV module, it is seen that Blas model is in good correlation with empirical values for the PV module (Fig. 3 and Fig.4).

12th day of July that was a clear day was chosen to represent behavior of the KA58 a-Si PV module in summer season. On that day, 1090W/m^2 plane of array irradiation is measured at noon and temperature of the PV module raised up to 61ºC. Fig. 3 shows variation in current-voltage for four different irradiation levels for the KA58 a-Si photovoltaic module.

As seen in Fig. 3, currents measured at noon are higher than those provided by the manufacturer under STC. The reason is the fact that irradiation is higher than that in STC by 9% as well as temperature of the PV module is measured as 36ºC, higher than 25⁰C.

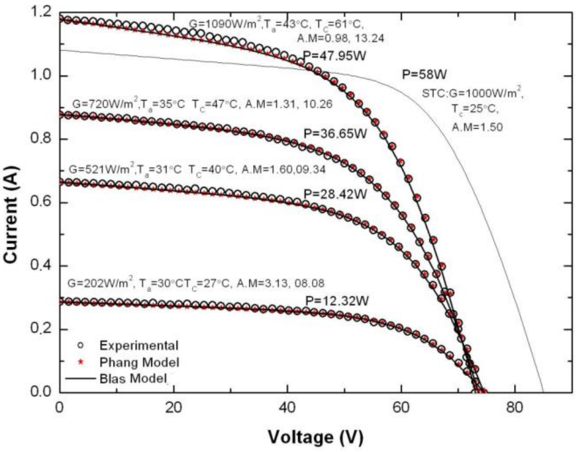

Fig. 3. The current-voltage characteristics of the photovoltaic module at 12nd of July

The measured open circuit voltage is lower that provided by the manufacturer under STC because temperature coefficient of open circuit voltage is negative. It was calculated that power of 47.79W could be drawn from the photovoltaic module on 12nd of July at 13.24 during noon time in which the highest irradiation was measured. This is 17% below the value provided by the manufacturer under STC.

8th of January that was a clear day was chosen to represent behavior of the KA58 a-Si photovoltaic module in winter season. It is seen that the experimentally measured current-voltage values are correlated with the obtained values by the used models (Fig. 4).

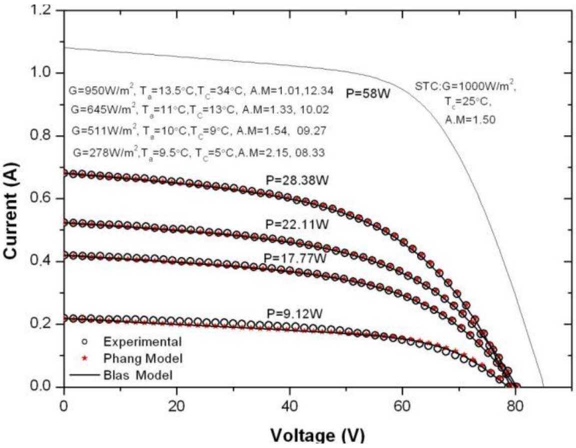

Fig. 4. The current-voltage characteristics of the photovoltaic module at 8th of January

Although the PV module temperature measured under the highest irradiation is very close to the value obtained under STC, the generated current is low due to the variance in the solar spectrum. Therefore, power, which might be generated from the PV module under 950W/m^2 plane of irradiation, is also low. In fact, it is only half of the value provided by the manufacturer under STC.

As seen in Fig. 3 and Fig.4, because the values, which are obtained by using Blas method, are consistent with the empiric values under winter and summer conditions, parameters for the solar cell and PV module may be calculated by using Equation sets from Eq.5 to Eq.9 closer to the values under the operating conditions.

3.1. Variations in Series Resistance

Series resistance values for the KA58 a-Si thin film PV module decrease logarithmically according to Eq.10 with irradiation. Herein, r_{S1} and r_{S2} are coefficients representing variation in series resistance, which vary depending on months (r_{S2} is calculated as positive only for January).

$$R_S = r_{S1} + r_{S2} \times \ln(G) \tag{10}$$

Lower values are preferred for series resistance. Therefore, series resistance value decreases under high irradiation levels with the contribution of the increasing temperature of the PV module and the increasing irradiation contributes to performance of the PV module. Fig. 5 shows variation of series resistance with irradiation calculated on the selected clear days during a year for the KA58 a-Si PV module. The series resistance values higher than 10Ω were calculated under low irradiation levels up to 500W/m^2. In the KA58 a-Si PV module, the series resistance values, which were calculated under irradiation values higher than 300W/m^2, are lower that (8.39Ω) provided by the manufacturer (Table 1).

For the KA58 a-Si PV module, the coefficients given in Eq.10 vary depending on months according to the result of the regression analysis conducted by using the least-square method for the values given in Fig.5; the general expression was calculated as the following.

$$R_S = 57.658 - 7.558 \times \ln(G) \tag{11}$$

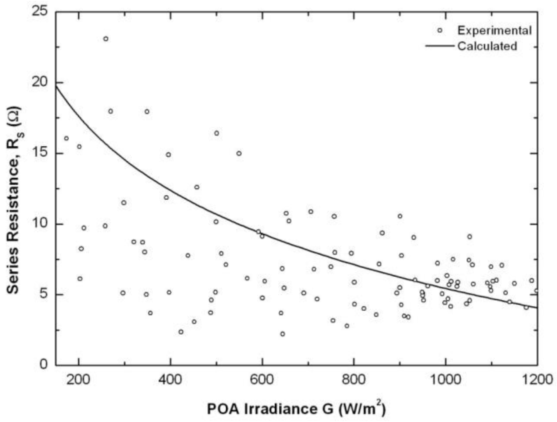

Fig. 5. Irradiation dependencies of the measured and calculated series resistance values

3.2. Variations in Series Resistance

Parallel resistance (R_{SH}) expresses leakage currents in a solar cell or photovoltaic module and they are parameters affecting performance. Departing from the gradient of current-voltage curve around the short circuit current, the parallel resistance value may be calculated by using Eq.9. It is seen according to the calculations made under different conditions that the gradient of current-voltage curve around the short circuit current decreases as parallel resistance value of the photovoltaic module increases. Because leakage currents are not desired in a solar cell or a photovoltaic module, parallel resistance should be kept higher as much as possible. $R_{SH} = \infty$ is accepted for an ideal solar cell. It is seen in the photovoltaic module under test that the parallel resistance, R_{SH}, depends on the irradiation level G and temperature of the solar cell/module, T_C , logarithmically according to Eq.12.

$$R_{SH} = r_{SH1} + r_{SH2} \times \ln(G) \tag{12}$$

Herein, r_{SH1} and r_{SH2} are coefficients representing variation in parallel resistance, which vary depending on months. Variation of parallel resistance value is seen on current-voltage curve more clearly. In the KA58 a-Si photovoltaic module, a decrease occurs in voltage as soon as the current at the maximum power point increases and the place of this point moves toward lower voltages and a bit higher currents on the current-voltage curve.

In the KA58 a-Si photovoltaic module, the calculated resistance values are in the interval of 400-1700Ω. It is in the calculations made up to irradiation level of 400W/m^2 that parallel resistance values are calculated between 900 and 1300Ω while they are lower than 700Ω for the irradiation higher than 600W/m^2. The manufacturer's parallel resistance value for the KA58 a-Si photovoltaic module is 1050Ω (Table 1). Fig. 6 shows variation in the values calculated under different irradiation levels during a year. The highest values for parallel resistance were calculated in August in which ambient temperature elevated to 40ºC and temperature of the photovoltaic module reached to 70ºC. They increase up to 1700Ω under low irradiation levels.

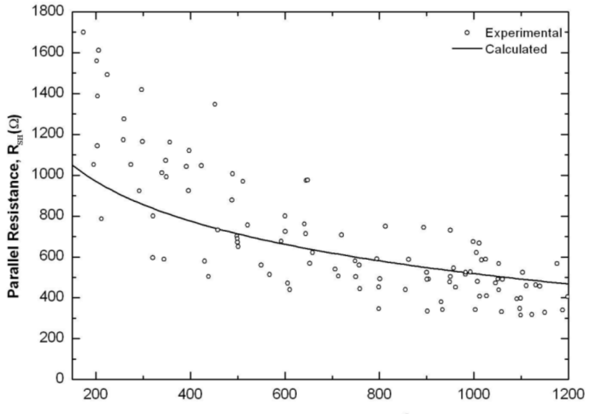

Fig. 6. Irradiation dependencies of the measured and calculated shunt resistance values

It is determined according to the calculations that the general Equation showing variation of parallel resistance value with irradiation in Eq.13 for the KA58 a-Si photovoltaic module.

$$R_{SH} = 2455.18 - 280.31 \times \ln(G) \tag{13}$$

3.3. Variations in Modified Ideality Factor

Modified ideality factor (a) is one of the important parameters affecting performance of a solar cell and PV module. Modified ideality factor may be calculated by using Eq.8 with the help of current-voltage curve. Variation in modified ideality factor does not change short circuit current of the solar cell or PV module; however, open circuit voltage vary linearly with modified ideality factor.

According to the calculations made for the KA58 a-Si PV module, the modified ideality factor intends to increase with the irradiation level (Fig. 7). According to the monthly regression analysis, it is seen that variation of modified ideality factor with irradiation level is consistent with Eq.14 provided that coefficients of a_1 and a_2 take different values depending on months.

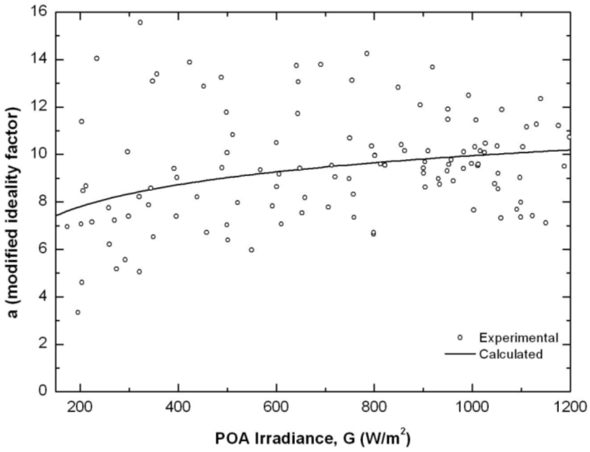

Fig. 7. Irradiation dependency of the measured and calculated modified ideality factor

$$a = a_1 \times e^{a_2 \times G} \tag{14}$$

However, in the analysis conducted for a period of 12 months, the general expression of the modified ideality factor with irradiation for the KA58 a-Si PV module is expressed in Eq.15 and irradiation dependency is shown in Fig.7.

$$a = a_0 - a_1 \times e^{a_2 \times G} \tag{15}$$

$$a = 11.083 - 6.174 \times e^{-0,00199 \times G} \tag{16}$$

Modified ideality factor for the KA58 a-Si PV module was calculated as 5.72 at 25^{0}C by using the diode ideality factor provided by the manufacturer as 2.21 under STC. The modified ideality factor value varies between 4 and 14 during the test period of 12 months. Fig. 7 shows its variation with the irradiation. It decreases with the irradiation in December, January, March and April (a_2 <0) while it increases in other months (a_2 >0).

3.4. Variations in Dark Saturation Current

Variation in dark saturation current does not change the short circuit current in a solar cell or a PV module; however, it causes the solar cell or PV module to work at lower voltages. The voltage on the maximum power point and the open circuit voltage decreases. As the dark saturation current increases, the maximum power point moves toward lower voltages; consequently, fill factor (*FF*), which equals to the maximum power over the product of short circuit current and open circuit voltage, decreases.

Temperature dependency of the PV module depends on the solar cell material as given in Eq.17. Dark saturation current (I_O), of a solar cell or a PV module is given as the following according to the data provided by the manufacturer under STC.

$$\frac{I_O}{I_{O,ref}}=\left(\frac{T_C}{T_{C,ref}}\right)^m\times\exp\left[\frac{E_G}{a_{ref}}\left(1-\frac{T_{C,ref}}{T_C}\right)\right] \tag{17}$$

Herein, it is $T_{C,ref}$=25ºC solar cell/module temperature, $I_{O,ref}$ is the dark saturation current under STC and E_G is the band gap of the semi-conductor of which the solar cell is made and *m* is a coefficient, which might take values between 2 and 4 and shows temperature dependency of dark saturation current [11].

According to the calculations, dark saturation current is within different intervals between 297 and 303 K in summers and winters. Table 2 shows the values obtained for the KA58 a-Si PV module.

Very high dark saturation current was calculated for the KA58 a-Si PV module compared with that provided by the manufacturer under STC. This may increase up to 1 mA in winter while the value provided by the manufacturer under STC is 222 nA that is approximately 1/5000 of the calculated value.

Table 2. Calculated dark saturation current interval values in summer and winter months for KA58 a-Si module at 297-303K

December, January, February	June, July, August	Value at STC
0.1-1.0 mA	5.0-29.0 µA	229 nA

3.5. Variations in Light Generated Current

Light generated current, I_L, is proportional to irradiation level on the solar cell/module. Operating temperature of the PV module, T_C , and the air mass (AM) due to its effect on solar spectrum. Light generated current under STC may be calculated at any irradiation *G* and operating temperature T_C as [12]

$$I_L=\frac{G}{G_{ref}}\left[I_{L,ref}+\mu I_{SC}\left(T_C-T_{C,ref}\right)\right] \tag{18}$$

Short circuit current and open circuit voltage of the PV module will increase with increasing light generated current. Because open circuit voltage depends on the current logarithmically; an increase in open circuit voltage will be lower than that in the short circuit current. Light generated current values for different irradiation levels for the KA58 a-Si PV module was calculated and the variation is shown in Fig. 8 for 12 months test period.

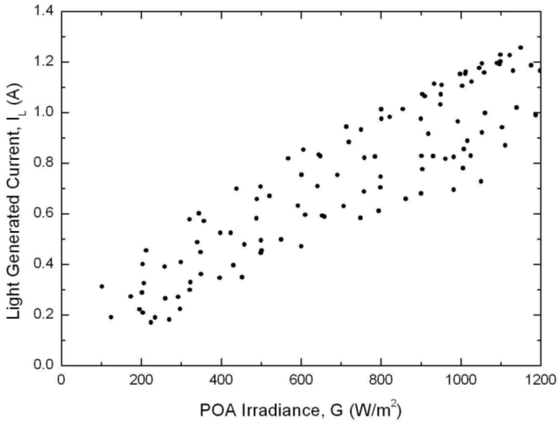

Fig. 8. Irradiation dependency of light generated current

Because the light generated current is directly proportional to irradiation level, the photovoltaic module's short circuit current and open circuit voltage will increase.

Effects of seasons on the KA58 a-Si PV module are very clear as seen in Fig. 8. There are differences up to 40% between light generated currents under same irradiation levels but different operating temperatures. Values calculated in September represent upper part of the distribution in Fig. 8 while those calculated in January represents lower parts.

In this study, it is shown that the single-diode model is successfully applicable to PV modules consisting of amorphous silicon thin film solar cells successfully with the help of modified ideality factor, which is known as curve parameter including temperature. Variations of the parameters affecting performance of the KA48 a-Si thin film PV modules measured during a period of 12 months with irradiation were determined.

4. Conclusion

The current-voltage curves of an a-Si module are taken for a year from April to May at the Mugla Sıtkı Kocman University PV Outdoor Test Site. Single diode model is proposed to explain the current-voltage curves of thin film solar cells and modules. The relationship between the environmental seasonal variations and internal parameters were analyzed. The following points were clarified:

1. In summer season the calculated power of the selected power of the tested module is lower than the value given at STC because of the high operating temperature.

2. The series resistance values higher than 10Ω were calculated under lower irradiation levels up to 500W/m^2. In the KA58 a-Si photovoltaic module, the series resistance values, which were calculated under irradiation values higher than 300W/m$_2$, are lower that (8.39Ω) provided by the manufacturer.

3. In the KA58 a-Si photovoltaic module, the calculated resistance values are in the interval of 400-1700Ω. It is in the calculations made up to irradiation level of 400W/m^2 that parallel resistance values are calculated between 900 and 1300Ω while they are lower than 700Ω for the irradiation higher than 600W/m^2. The manufacturer's parallel resistance value for the KA58 a-Si photovoltaic module is 1050Ω.

4. The modified ideality factor for the KA58 a-Si photovoltaic module was calculated between 4 and 14 during the test period of 12 months.

5. Very high dark saturation current was calculated for the KA58 a-Si photovoltaic module compared with that provided by the manufacturer under STC. Calculated values are in mA scale while the given value is in nA scale.

6. There are differences up to 40% between light generated currents under same irradiation but different operating temperatures.

References

[1] W. Hoffmann and S. Teske, Solar Generation IV-,Greenpeace, EPIA, Hamburg; 2007.

[2] EPIA, Global Market Outlook for Photovoltaics until 2014; May 2010.

[3] M.A. Mannan, M.S Anjan., M.Z. Kabir, "-Modeling of currentvoltage characteristics of thin film solar cells ", Solid-State Electronics, vol. 63, pp. 49-54, September 2011.

[4] M Burgelman., J. Poortmans, V. Arkhipov, Thin film solar cells: fabrication, characterization and applications. England: Wiley & Sons; 2006, ch 7.

[5] C. Oguz., Measurement and Analysis of Solar Irradiation at Mugla Province (in Turkish), MSc Thesis, Mugla Sıtkı Kocman University, Mugla, Turkey. 1999.

[6] J. A. Duffie and W. A. Beckman., Solar Engineering of Thermal Processes, third ed. Wiley Interscience,Hoboken, New Jersey; 2006, ch 23.

[7] D. K. Schröder, Semiconductor Material and Device Characterization, third ed. Wiley Interscience, Hoboken, New Jersey; 2006, ch 4.

[8] D.S.H Chan and J.C.H Phang, "Analytical methods for the extraction of solar-cell single- and double-diode model parameters from I-V characteristics ", IEEE Transactions on Electron Devices, vol. 34 Issue:2, pp. 286-293, 1987.

[9] M.A. de Blas, J.L. Torres, E. Prieto and A. García, "Selecting a suitable model for characterizing photovoltaic devices ", Renewable Energy, vol. 25, Issue: 3, pp. 371-380, March 2002.

[10] D. M. Spinner, Instruction Manuel: Solar Measuring System for Characterisation of Solar Cells (V 2.0 1/2003), Freiburg, Germany; 2003.

[11] W. de Soto, S.A. Klein and W.A. Beckman, "Improvement and validation of a model for photovoltaic array performance ", Solar Energy, Vol. 80, Issue:1, pp. 78-88, January 2006.

[12] T.U. Townsend, A Method for Estimating the Long-Term Performance of Direct-Coupled Photovoltaic Systems, MSc Thesis, University of Wisconsin, Madison, USA, 1989.