E3S Web of Conferences **140**, 04013 (2019)
*EECE-2019*
https://doi.org/10.1051/e3sconf/201914004013

# Mathematical modeling of parameters of solar modules for a solar power plant 2.5 MW in the climatic conditions of the Republic of Cuba

*Daniel* Guerra[1] and *Emiliia* Iakovleva[1,*]

[1]Department of Electrical Engineering, Saint-Petersburg Mining University, 2, 21st Line, St Petersburg, 199106, Russian Federation

**Abstract.** Today, the problem of increasing the efficiency of solar panels is relevant. The parameters and characteristics of solar modules are analyzed using computer modeling methods. Many contemporary scientists are busy with the problem of modeling different solar modules in different conditions. This paper presents the results of mathematical modeling in the Matlab software environment of photoelectric modules of the DSM-240-C model. Based on the obtained simulation results, it seems possible to study the characteristics of solar modules depending on various external and internal factors – temperature and illumination. Also in this paper, we present the results of a full-scale experiment of photovoltaic modules that are part of a 2.5 MW solar power plant operating in the Republic of Cuba. The results of the experiment confirm the effectiveness of the simulation.

## 1 Introduction

Today, one of the strategic tasks facing the Government of the Republic of Cuba is to increase the share of electricity received from renewable energy sources (RES). The goal of this program is the country's energy independence. This is due to the instability of hydrocarbon prices, as well as the lack of profits from the production of electricity by traditional methods. The construction of solar power plants in the country is widespread due to a number of advantages: renewability, abundance, constancy and availability of resources, concern for the environment, sound insulation and energy saving. However, solar power plants have two important drawbacks: variable characteristics and dependence on energy production in the face of climate change [1, 2].

In connection with the expansion of the field of application of solar PV modules, in some cases there is a need to accurately determine their parameters and characteristics. To analyze the characteristics of specific solar modules at different levels of illumination and temperature values, it is advisable to use the method of computer simulation.

Many groups of scientists are involved in modeling the I – V characteristics and parameters of photovoltaic panels. In [3], the results of mathematical and computer simulation of an equivalent circuit with a single diode were analyzed. In [4], simulation results for a polycrystalline silicon solar panel are presented.

The article presents the procedure for developing a simulation model of photovoltaic modules in a Matlab / Simulink environment. The simulation model is based on a five-parameter analytical model of the current-voltage characteristics of the solar cell. The developed model allows us to study the current-voltage and current-voltage characteristics of solar modules depending on the levels of solar radiation intensity, temperature, short circuit current, open circuit voltage, internal resistance of solar cells, and also a diode parameter. The discrepancy between the data of the simulation results and the technical characteristics does not exceed 5%.

## 2 Materials and methods

### 2.1 Mathematical model of a photovoltaic cell

Solar photovoltaic modules and solar photovoltaic batteries (SB) consist of many separate solar photovoltaic cells (SEs), which are connected in series and in parallel in order to provide the required output current and voltage values. According to [5], a solar photovoltaic cell is a solar cell based on a photoelectric effect that converts the energy of solar radiation into electrical energy. The action of the photocell is based on the phenomenon of the internal photoelectric effect [6, 7].

The process of separating the electron-hole pairs generated by light quanta at the p-n junction underlies the process of generating electric current in solar cells.

It has been established that the intensity of solar radiation affects the magnitude of the output current, and temperature affects the output voltage of the solar cell [8]. So, with a decrease in the intensity of the light flux by a factor of 2, the short-circuit current of an SC decreases by a factor of 2, while the open circuit voltage varies slightly. There is a temperature coefficient that

* Corresponding author: em88mi@gmail.com

https://doi.org/10.1051/e3sconf/201914004013

takes into account the temperature difference and is about several milliamps per degree Celsius.
The mathematical model of the photoelectric element is built on the basis of the classical equivalent equivalent circuit with lumped parameters (Fig. 1). This equivalent circuit includes a photocurrent generator, a diode, a shunt (Rsh), and a series (Rs) resistance. Satisfactory accuracy of the model can be obtained provided that the values of the internal resistances of the photocells are known. As a rule, during modeling, systematic deviations of the theoretical I – V curve from the experimental one are observed, which are the result of variable values of current densities and voltage gradients.

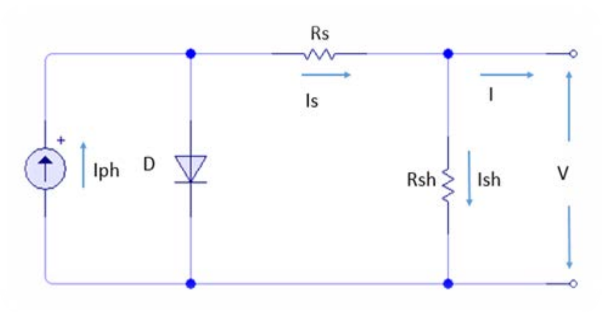


**Fig. 1.** Equivalent solar cell circuit.

The relationship between the current I and the voltage V of the equivalent circuit can be found by equating the current value of Iph and the current of the diode Id, then the working current I will be as follows [9].

$$A = e^{Voc/n*VT} - 1 \quad (1)$$

$$A = e^{Isc*Rs/n*VT} - 1 \quad (2)$$

$$I_{sc} = I_{scm}*N_{cp} + \beta*(T_c - T_{stc}) \quad (3)$$

$$V_{oc} = V_{ocm} - 0.0023*(T_c - T_{stc})*N_{cs} \quad (4)$$

$$\begin{aligned} I &= ((I_{sc}*(1 + R_s/R_{sh}) - V_{oc}*(B/A))/ \\ &/(1 - B/A))*G/G_{stc} - (((I_{sc}*(1 + R_s/R_{sh}) - \\ &-V_{oc}*B/A)/(A - B)) - V_{oc}/A*R_{sh})* \\ &*(e^{(V + I*Rs)/n*VT} - 1) - (V + I*R_s)/R_{sh} \end{aligned} \quad (5)$$

Where: $R_S$ - series resistance [ohm], $R_{Sh}$ - parallel resistance [ohm], *n*- ideality factor , $I_{SC}$- short circuit current under normal operating conditions (STC)[A], $V_T$ - thermal diode voltage [mV], *V* - operating voltage [V], *I* - working current [A], $V_{OC}$ – open circuit voltage under standard test condition (STC )[V], $\boldsymbol{\beta}$ - temperature coefficient of short circuit current, Gstc solar radiation under normal operating conditions (STC) [W/m$^2$], G - solar radiation [W/m$^2$], $N_{SC}$ – the number of solar cells in the series in the solar module [ohm], $N_{CP}$ - the number of solar cells in parallel in the solar module [ohm], $T_C$ - panel working temperature [°C], $T_{stc}$ - battery temperature under standard test conditions [25°C].

The current source $I_{ph}$ is a photocurrent depending on the radiation intensity, diode D describes the current flowing through an imperfect (with ideality factor n) p-n junction of the solar battery. The model includes parasitic parameters of the photocell structure - series resistance *Rs* and parallel resistance $R_{sh}$. The series resistance *Rs* depends on the manufacturing technology of the solar module and greatly affects its characteristics (Figure 5), when *Rs* decreases, the duty cycle *FF* and the maximum power $P_{max}$ decrease.

### 2.2 Simulation of a solar module in a Simulink/Matlab environment

Using the mathematical model described above, one can study the current-voltage characteristics of certain solar cells. To solve such problems, it is reasonable to use computer programming methods. Matlab software implements the principle of visual programming. The Simulink library is designed specifically for modeling electrical processes of varying complexity.

The Santiago de Cuba photovoltaic power plant currently has 10400 photovoltaic panels (SMC-240-C) connected in series and in parallel to form the rows of solar panels that make up the station's solar generator. Each section of the solar generator (130 in total) consists of 4 parallel structures of 20 solar panels connected in series.

**Table 1.** The technical characteristics of the solar panel (DSM-240-C module).

| | |
|---|---|
| Maximum Power | 240 W |
| Open terminal voltage | 37 V |
| Short circuit current | 8.54 A |
| Voltage at maximum power | 29.8 V |
| Current at maximum power | 8.19 A |
| Temperature Coefficients Isc | +0.0.65 %/*C |
| Temperature Coefficients PM | 0.43 %/*C |
| Temperature Coefficients Voc | -0.34 %/*C |
| Series resistance | 0.3546 Ω |
| Parallel resistance | 337.822 Ω |
| Silicon type | Mono-cristal |

The implementation of this equation 5 in the Matlab / Simulink environment is presented in Figure 2.

## 3 Results and discussion

### 3.1 Simulation results in Matlab Software

The developed model makes it possible to fix the main parameters of the solar module. The modeling did not take into account the possibility of partial dimming of the surface of the solar module. This limitation makes it possible to apply classical analytical expressions. Figures 3-6 show the simulation results. Figure 3 shows a family of current-voltage characteristics at a constant

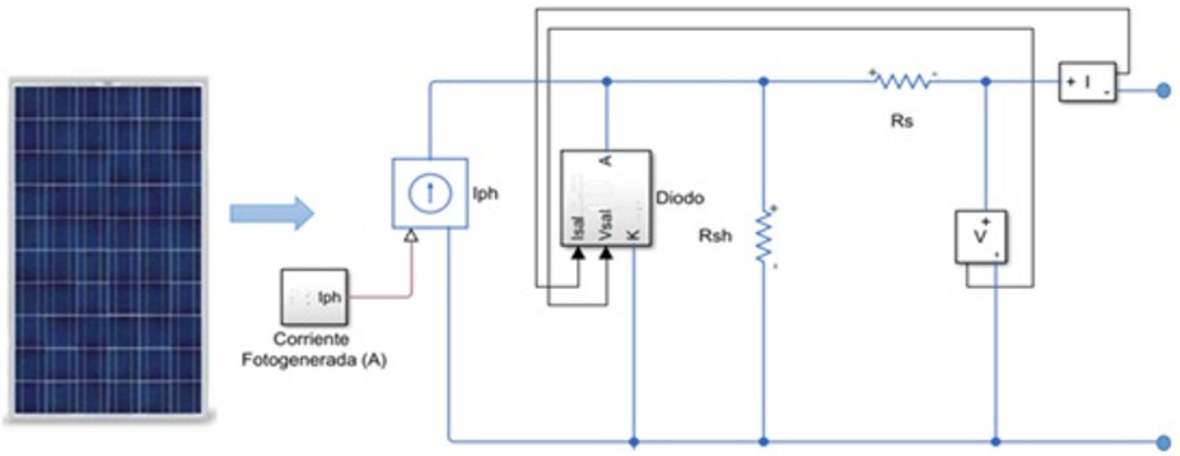


**Fig. 2.** Solar Module Diagram (DSM-240-C) at Matlab Simulink.

temperature of 25 ° C and variable solar radiation from 100 to 1200 W/m$^2$ with a step of 100 W/m$^2$.

Figure 3 shows that the simulations performed on the solar panel (DSM-240-C) were performed for high values of solar radiation (up to G = 1200 W/m$^2$), since values have been detected in the region of study about 1100 W/m$^2$ in the summer months. These values are justified and are less than the solar constant which is 1365.6 W/m$^2$.

Figure 3 shows the dependences of short circuit current, open circuit voltage and maximum solar cell power on solar radiation. Short circuit current and maximum power are linearly dependent on the magnitude of solar radiation. The maximum values of power, voltage and current are achieved with a solar flux value of 1200 W/m$^2$. When insolation drops by 100 W/m$^2$, the values of short circuit current and power drop by an average of 8%. While the open circuit voltage depends on illumination to a lesser extent and practically does not change.

Figure 4 presents on a hot day at 50ºC (exceeding the standard operating by 25 degrees), the maximum panel power will decrease by about 15.7 %. with increasing temperature, the efficiency of solar panels decreases. At the same time, the opposite situation occurs in spring when the temperature is below 25ºC: energy production can then be greater than the nominal maximum power Pm. That is, in this case, the cooling of solar modules positively affects their performance. Now we understand that the effectiveness of modules can vary at different times of the year.

The created model allows you to build a volt-watt characteristic of the solar cell, taking into account changes in temperature and solar radiation. Based on the results obtained, a point is determined on the characteristic at which the power reaches its maximum value. It should be noted that the short-term predicted values of temperature and solar radiation from online climate servers. Therefore, it is possible to make a forecast of the generated power of a solar cell at any time or for a certain interval of a day in advance (Fig. 3-4).

Based on the results obtained, the following conclusion can be drawn - a decrease in the series

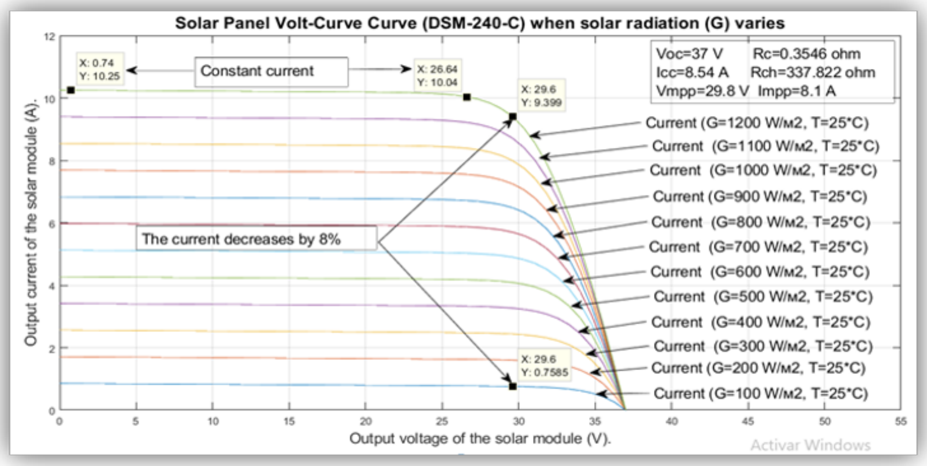


**Fig. 3.** Volt-ampere characteristic of a solar cell operating with various solar radiation.

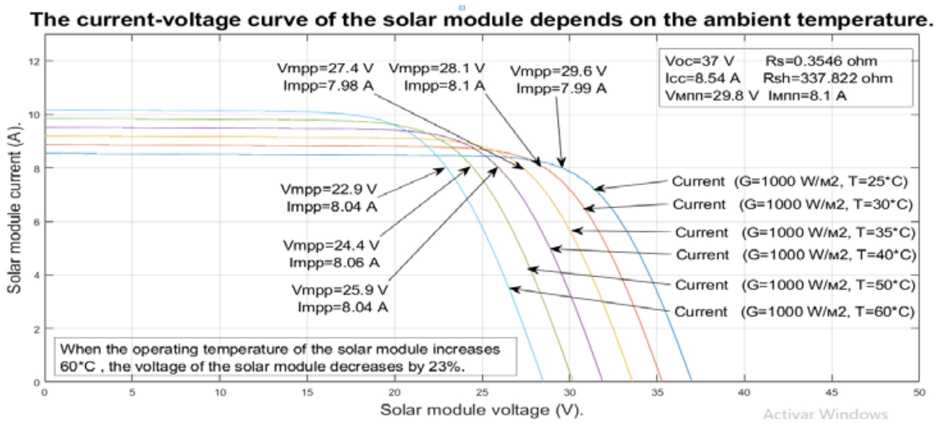


**Fig. 4.** Volt-ampere characteristic of a photocell operating at different operating temperatures.

resistance leads to a decrease in the maximum power of the solar module by 5%. A decrease in parallel resistance leads to a decrease in the maximum power of the solar module by 4%.

The graphs presented below reveal how much the power of the solar module can affect the variation of the internal resistance of the solar module. This effect is closely related to the degradation experienced by the

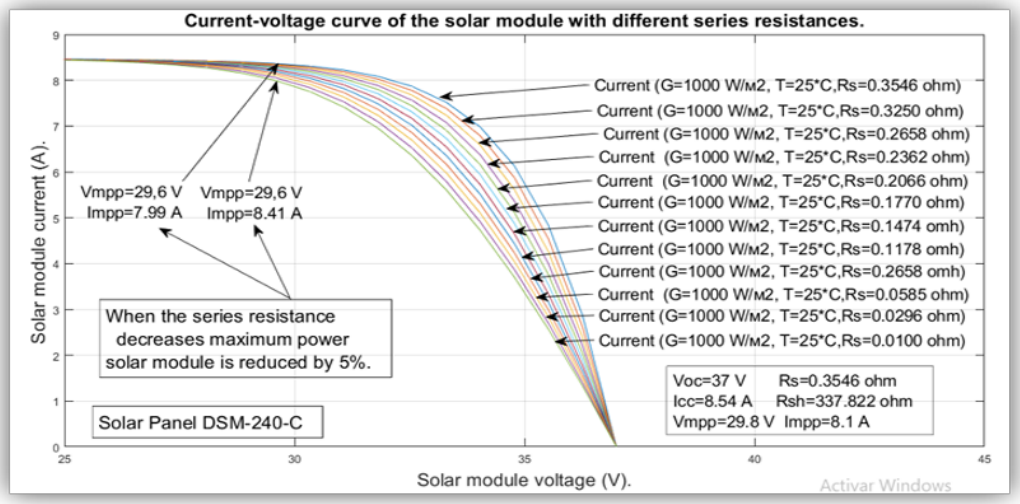


**Fig. 5.** The current-voltage characteristic of the photocell when the internal series resistance changes.

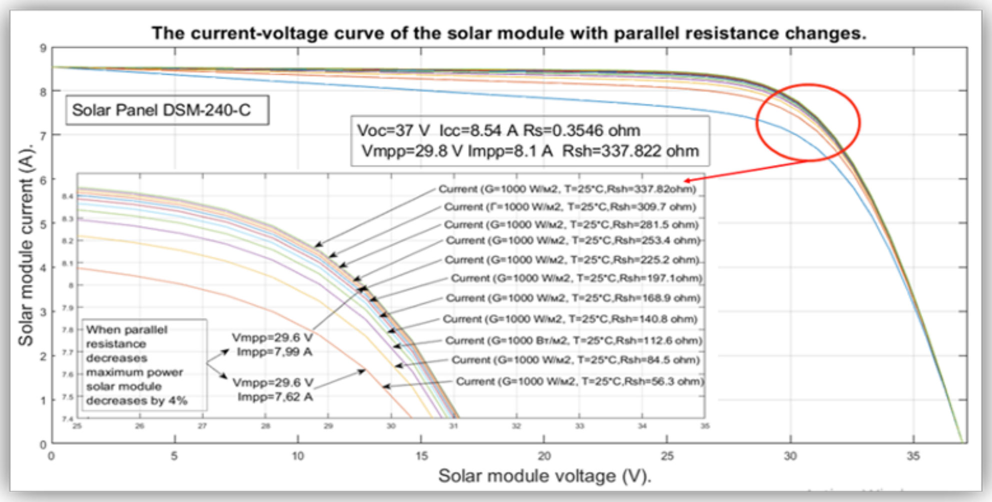


**Fig. 6.** The current-voltage characteristic of the photocell when the internal resistance is changed is parallel.

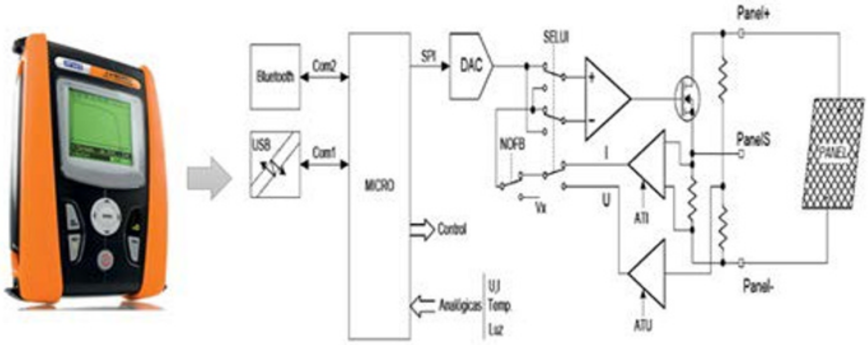


**Fig. 7.** Electrical diagram of the measuring equipment used (FLUKE model I-V 400).

solar modules in long time of exploitation.

### 3.2 Experimental studies in the climatic conditions of the Republic of Cuba

During the experiment, commercial equipment was used curve plotter FLUKE, model IV 400, Fig. 7. The use of this measuring device makes it possible to directly obtain in the field the most important characteristic of photovoltaic modules - the $I - V$ characteristic and its main characteristic electrical parameters of both the photovoltaic module and the group of photovoltaic modules [10].

This experiment had to be developed to verify the results obtained during the simulation using the mathematical model (equations 1,2,3,4 and 5) developed in the MATLAB software. After obtaining the current-voltage curve of the module at various operating temperatures and solar radiation conditions, these results will be compared with the data measured in real operating conditions.

The curve tracer used for this project works as follows. In order to build the V-I curve, two open-circuit measurements were made to measure the open-circuit voltage of the solar module and during a short circuit to measure the short-circuit current of the solar module.

Using this device, the current-voltage characteristics of solar modules in the climatic conditions of the province of Santiago de Cuba, the Republic of Cuba were analyzed. Solar panels are generally tested at 25ºC. Depending on the location, elevated temperatures can reduce effectiveness by 10-15% [11].

The experiment was carried out by connecting the solar panel (DSM-240-C) to the solar curve plotter, which has two sets of positive and negative electrical clamps, which are connected to the positive and negative terminals of the solar panel, and then to the equipment. a temperature sensor located at the rear of the solar panel is connected to measure the operating temperature of the solar panel, and a solar radiation sensor is connected, which is a standard sensor for measuring solar radiation reaching the surface of the panel.

Figure 8 shows a diagram of the connection of equipment to solar modules.


**Fig. 8.** Connection diagram of the device (I-V 400 model) to the solar module (DSM-240-C model).

The internal calculations developed by the team inform us about the main electrical characteristics of the solar panel in real operating conditions, since the data presented in the technical description of the solar panel are in nominal conditions at t = 25° C and solar radiation of 1000 W/m$^2$ [12, 13].

The measurements were developed at noon, because at this time the solar radiation reaches its maximum value, as well as the operating temperature of the solar panel, therefore, in order to assess the performance of the solar panel in actual use, it is necessary to expose the solar panels to the maximum climatic conditions existing in the region.

The results of the experiment at different times of the day are presented in Table 2. During the experiment, the following parameters were measured: $I_{SC}$ short circuit current, $V_{OC}$ open circuit voltage, solar radiation $G$, $T_C$ panel working temperature, voltage MPP $V_{MPP}$, current MPP $I_{MPP}$. All of these parameters affect the performance of the solar module.

According to measurements, the average power of the solar module at an operating temperature of 52 degrees decreases by 14%, and the voltage on average by 15%. Figure 9 shows how a change in the module affects the power of the module in actual use. The values obtained as a result of real measurements coincide with the values obtained by mathematical modeling in the Matlab solar module program.

**Table 2.** The results of the experiment.

| Time and date | Variable | Pmax | Voc | Vmpp | Impp | Isc | G | Tc |
|---|---|---|---|---|---|---|---|---|
| **08/05/2018 12:34** | MV * | 192.05 | 32.33 | 24.51 | 7.84 | 8.88 | 1002 | 61.1 |
| | STC ** | 223.30 | 36.86 | 28.36 | 7.87 | 8.58 | 1000 | 25.0 |
| **08/05/2018 12:38** | MV | 190.28 | 32.26 | 24.43 | 7.79 | 8.83 | 1022 | 60.3 |
| | STC | 216.44 | 36.72 | 27.79 | 7.79 | 8.37 | 1000 | 25.0 |
| **08/05/2018 12:43** | MV | 213.02 | 33.07 | 25.01 | 8.52 | 9.59 | 1115 | 57.4 |
| | STC | 221.27 | 37.15 | 28.58 | 7.74 | 8.35 | 1000 | 25.0 |
| **08/05/2018 13:06** | MV | 209.24 | 33.79 | 25.51 | 8.20 | 9.00 | 1062 | 50.1 |
| | STC | 219.19 | 36.93 | 28.58 | 7.67 | 8.30 | 1000 | 25.0 |
| **08/05/2018 13:07** | MV | 203.45 | 33.65 | 25.36 | 8.02 | 8.78 | 1036 | 51.3 |
| | STC | 219.12 | 36.93 | 28.93 | 7.57 | 8.30 | 1000 | 25.0 |
| **08/05/2018 13:15** | MV | 201.93 | 33.65 | 25.65 | 7.87 | 8.69 | 1026 | 51.1 |
| | STC | 219.33 | 36.93 | 28.72 | 7.64 | 8.29 | 1000 | 25.0 |
| **08/05/2018 13:15** | MV | 203.76 | 33.13 | 25.36 | 8.03 | 8.89 | 1033 | 55.0 |
| | STC | 223.49 | 36.79 | 28.51 | 7.84 | 8.38 | 1000 | 25.0 |
| **08/05/2018 13:15** | MV | 198.88 | 32.72 | 25.08 | 7.93 | 8.77 | 1012 | 56.8 |
| | STC | 224.35 | 36.72 | 28.36 | 7.91 | 8.47 | 100 | 25.0 |
| **08/05/2018 13:21** | MV | 197.22 | 32.67 | 24.58 | 8.03 | 8.72 | 1007 | 57.6 |
| | STC | 224.14 | 36.79 | 28.79 | 7.79 | 8.47 | 1000 | 25.0 |
| **08/05/2018 13:22** | MV | 197.22 | 32.67 | 24.58 | 8.03 | 8.72 | 1007 | 57.6 |
| | STC | 224.14 | 36.79 | 28.79 | 7.79 | 8.47 | 1000 | 25.0 |
| **nominal value** | **STC** | 240.00 | 37.00 | 29.80 | 8.06 | 8.54 | 1000 | 25.0 |
| **Average value** | MV | 200.705 | 32.994 | 24.507 | 8.026 | 8.887 | 1032.2 | 55.83 |
| | STC | 221.47 | 36.86 | 28.54 | 7.76 | 8.39 | 1000 | 25 |

As can be seen from the temperature and electrical characteristics of the solar battery (Table 2), the temperature coefficient of open circuit voltage (Voc Temperature Coefficient) is much higher than the temperature coefficient of short-circuit current (Isc Temperature Coefficient), and therefore, with increasing temperature, the voltage drop is greater than the increase in current (Figure 9). Therefore, the power of the solar battery, as the product of the amperage and voltage, decreases with increasing temperature, and the battery operates with less efficiency.

In mathematical modeling, a decrease in power by

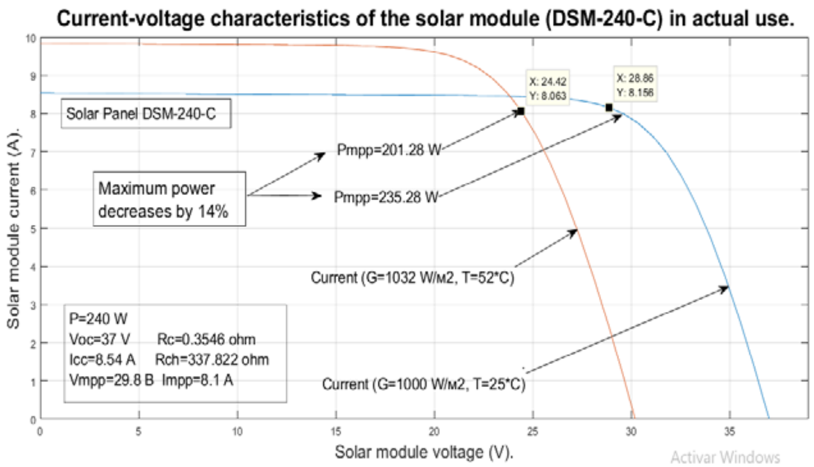


**Fig. 9.** Electrical Specifications of the Solar Module (DSM-240-C) in Actual Use.

15.7 % was obtained in the Matlab program, and in real measurements a decrease in power was obtained by 14.8%.

## 4 Conclusion

An increase in the temperature of the solar battery can lead not only to a decrease in the generated power, but also to the inability of the solar power station to function as a complete system. This is due to the fact that when designing a solar power plant, the selection of equipment is often carried out on the basis of only general technical characteristics specified in the technical documentation, excluding temperature characteristics [14].

Studies in real conditions of the solar module confirm the effectiveness of mathematical modeling performed in the Matlab program. With increasing temperature, the efficiency of solar panels decreases [15]. With increasing temperature, the electron flux increases, which causes an increase in current strength and a voltage drop. The voltage drop in this case is greater than the increase in current strength. Therefore, the total power is reduced, which leads to the fact that the panel works with less efficiency.

## References

1. I. Murashov, V. Frolov, M. Korotkikh and L. Ushomirskaya, MATEC Web of conferences **245,** 04003 (2018)
2. N.V. Obraztsov, D.I. Subbotin, V.E. Popov, V.Y. Frolov and A.V. Surov, Journal of physics: Conference series **1038(1),** 012137 (2018)
3. X.N. Nguyen and M.P. Nguyen, Environmental Systems Research, **4(1),** 24 (2015)
4. T. Selmi and R. Belghouthi, International Journal of Energy and Environmental Engineering, **8(4),** 273–281 (2017)
5. A. Smets, K. Jager, O. Isabella, R. Van Swaaij and M. Zeman, Solar Energy: The Physicsand Engineering of Photovoltaic Conversion, Technologies and Systems. UK: Uit Cambridge (2016)
6. A. Acevedo-Luna and A. Morales-Acevedo, Journal of Materials Science: Materials in Electronics, 1–7 (2018)
7. K. Vostrov, V. Frolov and E. Safonov, 22nd Symposium on physics of switching arc 2017-September, 182-185 (2017)
8. R. Kozakov, A. Khakpour, S. Gorchakov, G. Podporkin, V. Frolov, 21st Symposium on physics of switching arc 2015, 150-154 (2015)
9. F. Reyes-Caballero, F. Fernández-Morales and J. Duarte, Desarrollo e Innovación, **7(1),** 151-163 (2016)
10. S.A. Alghan, H. Almusawi and H. Geza, Matec Web of Conferences **126**, 03002 (2017)
11. A. I. Bardanov and T. V. Pudkova, Proc. 2019 IEEE Conf. Russ. Young Res. Electr. Electron. Eng. ElConRus (IEEE, 2019), 430-433 (2019)
12. D. Rusirwan and I. Farkas, Energy Procedia **57,** 39-46 (2014)
13. D. Icaza-Alvarez, C. J. Calle-Castro, F. Cordova-Gonzalez, A. Lojano-Uguna and J. F. Toledo-Toledo, in 6th International Conference on Renewable Energy Research and Applications (5), 620–625. San Diego: IEEE. (2017)
14. B.N. Abramovich, Journal of Mining Institute **229,** 31-41 (2018)
15. H. Rezk and E.S. Hasaneen, Ain Shams Engineering Journal, **6(3),** 873–881 (2015)