Mathematical modeling in MATLAB of a photovoltaic panel

T Pop, C Buzduga, R-D Pentiuc, V-C Ifrim, C Ungureanu

Faculty of Electrical Engineering and Computer Science
"Ștefan cel Mare" University of Suceava, Suceava, Romania

E-mail: teodor.pop@usm.ro, cbuzduga@usm.ro, radu.pentiuc@usm.ro, ifrimpv@gmail.com, costel@usm.ro

Abstract. With the increase in energy demand, the necessity for photovoltaic panels to be as efficient as possible has also increased. In order to achieve the highest possible performance, solar cells depend on a number of environmental elements such as: temperature, shading, cloudy weather, deposits on the surface, dust, solar irradiation, nighttime darkness, etc. All these factors ultimately result in a decline in photovoltaic panels performances. With the help of modeling and simulation programs, complex systems with high performance can be designed and realized, considering the advantage of avoiding manufacturing costs through their physical testing. Based on the electrical and thermal characteristics extracted from the Sanyo producer's data sheet, the proposed commercial photovoltaic module HIT-240HDE4, is implemented in the MATLAB environment under standard and real test conditions. The article presents the modeling and simulation in the MATLAB program of the proposed photovoltaic module, for the analysis of the electrical performances under the described conditions. Also, the article addresses the analysis issue of the operation considering the chosen module, under the same conditions.

1. Introduction

The decline of global fossil fuel stocks and the constantly increasing global warming effect, makes the alternative of renewable energies a topical field, an area that has acquired over time a special importance, being a viable alternative to obtaining clean energy, non-polluting for the environment, with a low maintenance cost. The greatest attention for alternative renewable energies is directed towards solar energy. Among the solar systems that are widely used we name two categories of technologies that use solar energy: the solar unit that converts the radiation captured from the sun into electricity (PV) and the solar thermal cell (ST), a method used to obtain hot water, used to heat residential spaces and industrial spaces [1-4].

A photovoltaic module is the main fundamental power conversion unit for the PV generator system. In order to have a superior efficiency of the PV module, the characteristic output depends largely on the solar insulation and the temperature of the cell, the module having nonlinear characteristics requiring its modeling (in order to be designed) and simulating the maximum tracking point power (MPPT) for photovoltaic system applications. Because the specific features of photovoltaic cells are influenced by irradiation and temperature, they are shaped by a circuit design. The manufacturers of the modules provide information about the components that make up these modules, but also about the PV characteristics, specifying certain points of them (current-voltage) called optimal operating points equivalent to a single point of maximum power [1-8].

A photovoltaic module has a complex behavior in different lighting conditions. A simulation model to examine the current, voltage and power relationship under different environmental conditions and partial shading conditions, is advantageous to be built. In order to be successful in modeling photovoltaic cells and PV modules, two categories are used: modeling based on mathematics, computer-assisted mathematical software (e.g., MATLAB) and the second category, modeling based on electronic components [9-16].

2. Photovoltaic panel characteristics

The modeled photovoltaic system is a commercial panel, SANYO HIT (Heterojunction with Intrinsic Thin layer), build out of thin mono crystalline silicone cells enclosed by ultra-thin layers of amorphous silicon. HIT cells and modules have a high efficiency of converting solar energy into electricity. These panels can generate more renewable energy than conventional crystal cell panels. Table 1 indicates the efficiency of cells and PV modules [17].

Table 1. Efficiency of HIT-240HDE4 panel.

PV model	Cell yield	Module yield
240HDE4-HIT	20,0%	17,3%

The features of Sanyo HIT-HDE4 240W photovoltaic panel are the following [17]:

- these modules have a high conversion efficiency;
- excellent temperature characteristics;
- in conditions of diffused or low light they have considerable efficiency.

Figure 1 represents a real image of the panels to be modeled and simulated in this paper.

Figure 1. Sanyo HIT-HDE4 240W photovoltaic panel.

Efficiency is an important thing to consider when comparing solar panels because it influences the quality of energy that can be captured from the sun. The best (optimal) conditions to obtain energy are on sunny days with low temperatures, although PV panels produce electricity in the absence of electrical radiation and at high temperatures [17], [18].

The electrical characteristics of the 240W Sanyo HIT HDE4 module are shown in Table 2. The conditions for standard tests are: cell temperature 25°C; irradiation 1000 W/m^2; air mass 1,5. The values presented in Table 2 are rated values [17].

Table 2. Electrical characteristics of the 240W Sanyo HIT HDE4 module.

PV electrical characteristics	HIT-240HDE4 module
Maximum power (Pmax) [W]	240
Maximum power voltage (Vpm) [V]	35.5
Open circuit voltage (Voc) [V]	43.6
Maximum power current (lpm) [A]	6.77
Maximum system voltage [Vdc]	1000
Short circuit current (Isc) [A]	7.37
Maximum over current rating [A]	15
Warranted minimum power (Pmin) [W]	228.0
Output power tolerance [%]	+10/-5
Temperature coefficient of Pmax [%/°C]	- 0.30
Temperature coefficient of Voc [V/°C]	- 0.109
Temperature coefficient of Isc [mA/°C]	2.21

The irradiance and temperature dependence of the 240W Sanyo HIT-HDE4 is shown in Figures 2 and 3 [17].

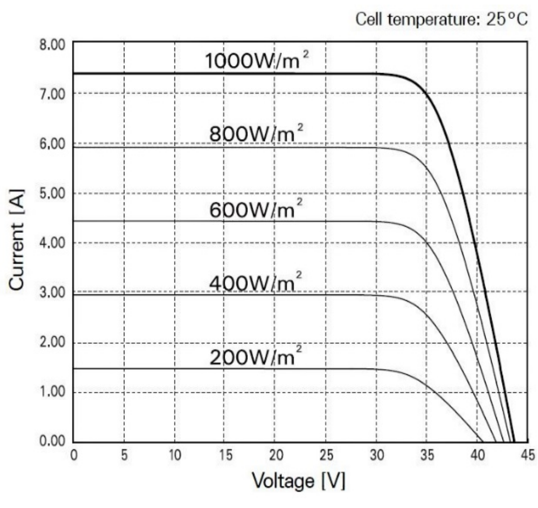

Figure 2. Irradiance dependence for a cell temperature equal to 25°C.

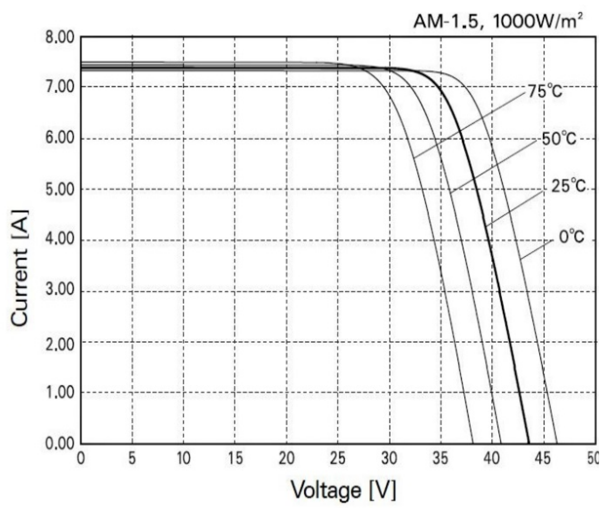

Figure 3. Temperature dependence on for a value of irradiance of 1000 W/m^2.

The following chapter deals with the realization and implementation of the functions specific to the MATLAB modeling environment and specific to the chosen PV panel module. A number of graphs have been plotted and analyzed considering fixed values and variable values of the outer temperature and of the solar irradiance, values from manufacturer's data sheet and others actually measured.

3. MATLAB modeling and simulation. Results

To determine the performances of the chosen PV panel system, the following conditions were introduced in MATLAB: the standard test conditions according to the equipment technical data sheet, the real irradiance measured with a SPN1 pyranometer and different values of the outside temperature. For each case, different performance curves were generated.

The equations implemented as specific functions in the MATLAB modeling environment are presented below [7], [11], [19].

The saturation current (I_0) associated to the PV panel can be assessed with the following equation:

$$I_0 = I_0(T_r)\left(\frac{T}{T_r}\right)^{\frac{3}{n}} e^{-\left(\frac{qAm}{nK}\left(\frac{1}{Tr}-\frac{1}{T}\right)\right)} \quad (1)$$

The current (I) of photovoltaic panel can be determined with the equation:

$$I = I_{ph} - I_0 e^{\left(\frac{V_{oc}+IR_s}{V_T}\right)} - 1 - \left(\frac{V_{oc}+IR_s}{R_{sh}}\right) \quad (2)$$

The thermal voltage (V_T) associated to the PV panel can be obtained with the equation:

$$V_T = \frac{N_s K T_{opt}}{q} \quad (3)$$

The photocurrent (I_{ph}) of the PV panel can be determined with the equation:

$$I_{ph} = (I_{sc} + K_i(T - T_r))\frac{G}{G_r} \quad (4)$$

In the begging of the analysis, the standard testing conditions of the PV panel were implemented in the simulation program according to the data sheet provided by the equipment manufacturer. According to standard test conditions the air mass is equal to 1.5, cell temperature equal to 25°C and irradiance valued at 1000 W/m^2.

In Figure 4 and Figure 5 are presented the graphs resulting from the determination of panel power by modeling according to the irradiance variation at the same outside temperature values provided by the panel producer.

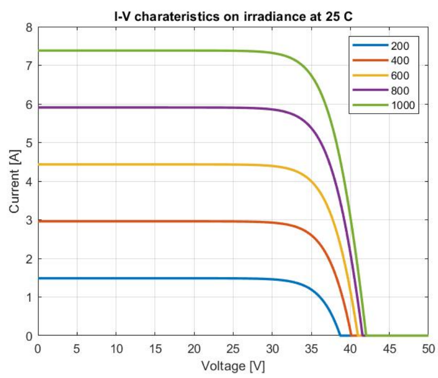

Figure 4. Current and voltage characteristics depending on the variation of irradiance and fixed temperature.

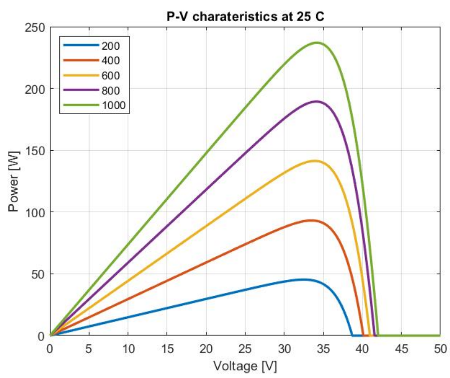

Figure 5. Power and voltage characteristics depending on the variation of irradiance and fixed temperature.

The results represented by the previous graphs are in line with the results delivered by the producer of the PV panel modeled in MATLAB. Also, the power generated after modeling the PV panel at a temperature of 25°C respectively at an irradiance of 1000 W/m^2 produced a power closed to 240 W which is in accordance with the electrical efficiency provided in the data sheet.

In Figure 6 and Figure 7 are presented the graphs resulting from the determination of panel power by modeling according to the temperature variation at the same irradiance, maximum value of irradiance provided by the panel producer.

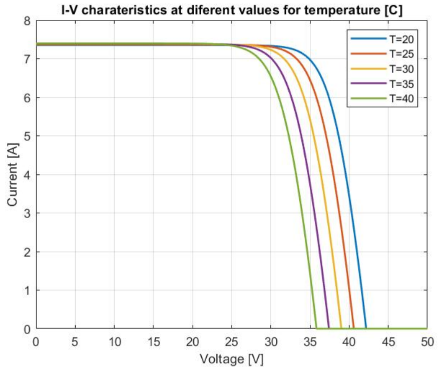

Figure 6. Current and voltage characteristics depending on the variation of temperature and fixed irradiance.

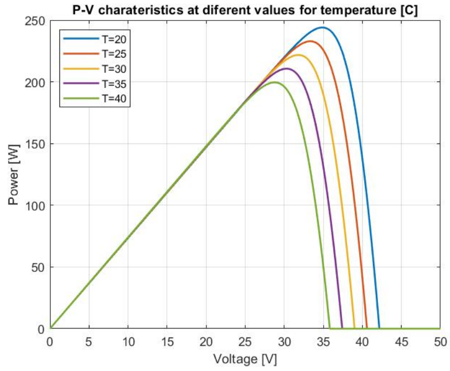

Figure 7. Power and voltage characteristics depending on the variation of temperature and fixed irradiance.

The graphics represented by Figure 6 and Figure 7 resulted from modelling a fixed irradiance of 1000 W/m^2 and by the variation of the external temperature at values ranging from 20 to 45°C. According to the graph of Figure 7 it is noticed that the power of the studied panel is higher, almost over 240 W, at the temperature of 20°C compared to the temperature of 25°C at the same fixed irradiance.

The initial analysis which accounted the data provided with the panel is continued with the analysis considering a measured value of irradiance equal to and different values of temperature. The value of irradiance and the values of the measured temperature used to continue the study of the chosen panel was part of a research conducted on 10.06.2022. Figure 8 graphically depicts the solar irradiance with the two components, total and diffuse. The maximum recorded value is 1389,57 W/m^2 for the total value and 448,83 W/m^2 for the diffuse one [18].

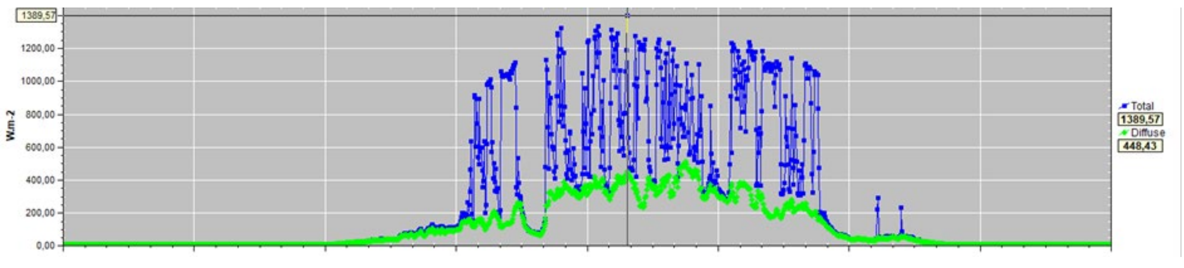

Figure 8. Real values of solar irradiance recorded with the SPN1 pyranometer [18]

In Figure 9 and Figure 10 are presented the graphs resulting from the determination of panel power by modeling according to the same irradiance of 1389,57 W/m^2 and the following values: 17°C, 22°C, 27°C, 32°C and 37°C of temperature.

The graphics represented by Figure 9 and Figure 10 resulted from modelling a fixed measured irradiance of 1389,57 W/m^2 and by the variation of the external temperature measured at the following values 17°C, 22°C, 27°C, 32°C and 37°C.

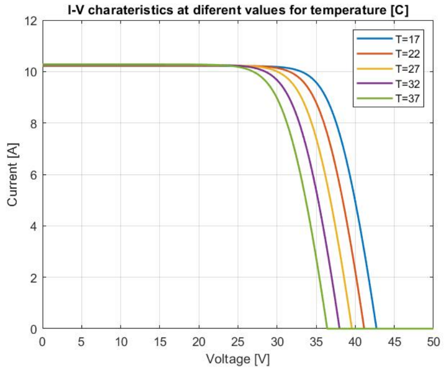

Figure 9. Current and voltage characteristics depending on the acquired values (fixed irradiance and variation of temperature).

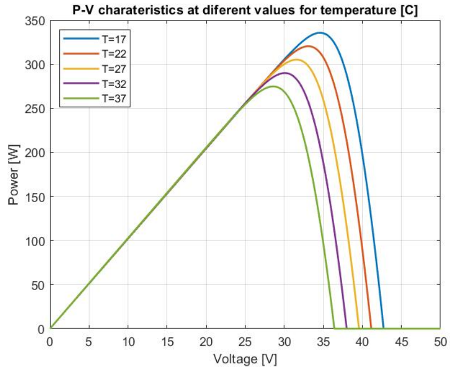

Figure 10. Power and voltage characteristics depending on the acquired values (fixed irradiance and variation of temperature).

According to the graph of Figure 10 the maximum value of the power equal to 240 W, provided by the technical data, is acquired at an irradiance of 1389,57 W/m^2 and a temperature of 37°C. Also, it is noticed that the power of the studied panel is higher, almost over 340 W, at the temperature of 17°C compared to the temperature of 37°C at the same fixed irradiance.

In Figure 11 and Figure 12 are presented the graphs resulting from the determination of panel power by modeling according to the same irradiance of 1389,57 W/m^2 and the value equal to 25°C of temperature.

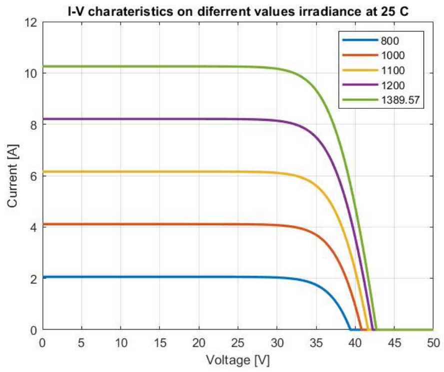

Figure 11. Current and voltage characteristics depending on the fixed measured values of temperature and irradiance.

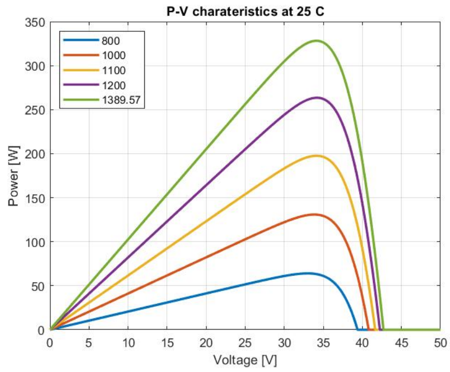

Figure 12. Power and voltage characteristics depending on the fixed measured values of temperature and irradiance.

The graphics represented by Figure 11 and Figure 12 resulted from modelling a fixed measured irradiance of 1389,57 W/m^2 and a fixed valued of the external temperature equal to 25°C. According to the graph of Figure 12 the maximum value of the power is equal to almost 325 W.

4. Conclusions

Using the MATLAB programming environment, the operating characteristics of a photovoltaic panel were obtained.

In order to compare the characteristics of the photovoltaic panel, there were used parameters taken from the technical data sheet of the photovoltaic panel and parameters physically measured at its operation. The mathematical relations, which were taken over from the specialized literature, were the basis for the realization and implementation of the MATLAB functions [20].

According to the achieved results we establish that the maximum power of the studied panel is reached at a lower exterior temperature and a higher irradiance. A higher external temperature decreases electrical performance because of losses through the Joule-Lentz effect.

For the development of the proposed study, in the future, the MATLAB/Simscape programming/simulation environment will be used, which contains a section specialized in the study of photovoltaic panels.

Nomenclature

Meanings of the equation's parameters:

I_0 – saturation current;
T – temperature;
T_r – reference temperature;
q – charge constant;
A_m – Air mas;
K – Boltzmann constant;
n – diode ideality constant;
I – current;
I_{ph} – photocurrent;
V_{oc} – open circuit voltage;
R_s – serial resistance;
R_{sh} – shunt resistance;
V_T – thermal voltage;
T_{opt} – optimal temperature;
N_s – number of cells;
G – irradiance;
G_r – reference irradiance;
K_i – temperature coefficient of Isc;
I_{sc} – short circuit current.

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