Artur BUGAŁA, Grażyna FRYDRYCHOWICZ-JASTRZĘBSKA

Poznan University of Technology Institute of Electrical Engineering and Electronics

Assessment of convergence between current – voltage characteristics of photovoltaic modules from mathematical calculations and measurements in real conditions

Abstract. *Based on equivalent two - diode solar cell circuit an algorithm for determining the current - voltage characteristics was developed and computer simulation was performed for selected silicon modules. The impact of electrical and thermal parameters of solar cells, area of the module, quality factors, number of cells connected series and parallel and impact of external conditions, especially density of solar radiation and the temperature was included. Measuring verification of current – voltage characteristics of selected PV modules was carried out in real conditions. The measurements of radiation power density on the surface of PV module were included. Obtained results confirmed the results of the calculations. (Assessment of convergence between current – voltage characteristics of photovoltaic modules from mathematical calculations and measurements in real conditions)*

Streszczenie. *Opracowano algorytm wyznaczania charakterystyk prądowo - napięciowych na podstawie dwudiodowego schematu zastępczego ogniwa i przeprowadzono symulację komputerową dla wybranych modułów krzemowych. W rozważaniach uwzględniono parametry elektryczne i cieplne ogniw, składających się na moduł, powierzchnię roboczą modułu, współczynniki jakości, liczbę ogniw połączonych szeregowo, jak i liczbę szeregów ogniw oraz wpływ warunków zewnętrznych, w szczególności nasłonecznienia i temperatury na pracę modułów. Przeprowadzono również weryfikację pomiarową charakterystyk prądowo - napięciowych wybranych modułów w warunkach rzeczywistych. Badania uzupełniono o pomiary gęstości mocy promieniowania na powierzchni modułu. Uzyskane wyniki pomiarów potwierdziły te otrzymane z obliczeń. (**Ocena zgodności pomiędzy charakterystykami prądowo – napięciowymi modułów PV na podstawie obliczeń matematycznych i pomiarów w warunkach rzeczywistych**)*

Słowa kluczowe: charakterystyki prądowo - napięciowe, model dwudiodowy, gęstość mocy promieniowania, parametry elektryczne.
Keywords: current - voltage characteristics, two - diode model, radiation power density, electrical parameters.

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Equivalent circuit of solar cell

For considerations two - diode cell circuit was proposed, shown in figure 1 [2,3,4], because of its higher precision in modeling solar cell than using simplified one - diode scheme. The second diode is connected parallel to the first and has different parameters [5,6].

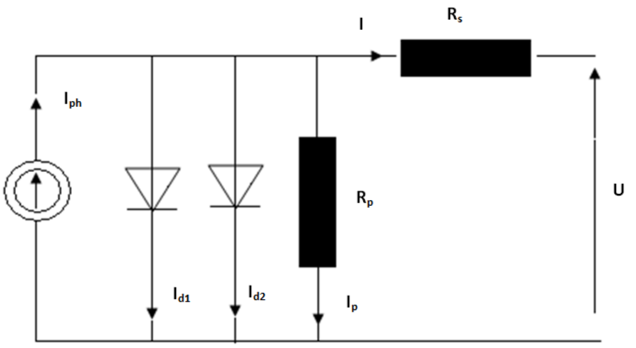

Fig.1. Equivalent two - diode cell circuit

Between the currents from equivalent cell circuit, according to Kirchhoff's current equation, there is a relationship:

(1) $$I = I_{ph} - I_{d1} - I_{d2} - I_p$$

The current source shown in figure 1, as a result of the photovoltaic phenomenon, generates I_{ph}. Its value is directly proportional to the radiation power density falling on the surface of solar cell:

(2) $$I_{ph} = I_{sc} \cdot (\frac{S}{1000}) + J_o \cdot (T - T_{ref})$$

where: I_{sc} – short - circuit current [A], T_{ref} - temperature [K] in standard test conditions, T - temperature of solar cell [K], J_o - diode temperature coefficient [A/K], S - solar radiation power density [W/m^2]. Diode current is described as:

(3) $$I_d = I_o \cdot [exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha \cdot k_B \cdot T}) - 1]$$

Due to the different parameters of both diodes (Fig.1), the currents described (3) have different values of diode quality factor α and – current I_o, where:

(4) $$I_o = I_{do} \cdot (\frac{T}{T_{ref}})^3 \cdot exp[\frac{q \cdot E_q \cdot m}{\alpha \cdot k_B}(\frac{1}{T_{ref}} - \frac{1}{T})]$$

and: R_s - series resistance [Ω], U - voltage on the load R [V], I_{do} - diode dark current [A], q - elementary charge [C], E_q - potential energy barrier depending on diode material [V], m - number of series connected cells, k_B - Boltzmann constant [J/K], α - diode quality coefficient.
Diode quality factor is a dimensionless value describing the degree of matching the solar cell to the ideal diode model. That coefficient indicates the participation of recombination and diffusion current in total photocurrent flow [7,8]. Its value is in the range of <1,2> (for ideal diode equals 1). It is described as:

(5) $$\alpha = \frac{q \cdot (U_2 - U_1)}{k_B \cdot T \cdot ln(\frac{I_2}{I_1})}$$

The current flowing through the parallel resistance:

(6) $$I_p = \frac{U + R_s \cdot I}{R_p}$$

Taking into account equations from (2) to (6), equation (1) can be written as:

(7) $$\begin{aligned} I = {} & I_{sc} \cdot (\frac{S}{1000}) + J_o \cdot (T - T_{ref}) - \\ & + I_{o1} \cdot [exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_1 \cdot k_B \cdot T}) - 1] - \\ & + I_{o2} \cdot [exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_2 \cdot k_B \cdot T}) - 1] - \frac{U + R_s \cdot I}{R_p} \end{aligned}$$

The equations are solved in an iterative way, therefore:

(8) $$I_{i+1} = I_i - \frac{f(I_i,U)}{\frac{df}{dI}(I_i,U)}$$

where:

(9) $$\frac{df}{dI}(I_i,U) = -I_{o1} \cdot \frac{R_s}{\alpha_1 \cdot k_B \cdot T} \cdot exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_1 \cdot k_B \cdot T}) - + I_{o2} \cdot \frac{R_s}{\alpha_2 \cdot k_B \cdot T} \cdot exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_2 \cdot k_B \cdot T}) - \frac{R_s}{R_p} - 1$$

Final iterative formula:

(10) $$I_{i+1} = I_i - \frac{f(I_i,U)}{x_1 - x_2 - \frac{R_s}{R_p} - 1}$$

where:

(11) $$x_1 = I_{o1} \cdot \frac{R_s}{\alpha_1 \cdot k_B \cdot T} \cdot exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_1 \cdot k_B \cdot T})$$

(12) $$x_2 = I_{o2} \cdot \frac{R_s}{\alpha_2 \cdot k_B \cdot T} \cdot exp(\frac{q \cdot (U + R_s \cdot I)}{\alpha_2 \cdot k_B \cdot T})$$

Open - circuit voltage is a logarithmic function of ratio of currents. Indirectly depends on the solar radiation of power density. The increase of temperature will cause reduction of U_{oc}. The voltage - current – temperature relationship can be written as:

(13) $$U_{oc} = \frac{k_B \cdot T}{q} \cdot ln(\frac{I_{ph}}{I_o} + 1)$$

(14) $$U_{oc} = V_T \cdot ln(\frac{I_{ph}}{I_o})$$

Open circuit voltage temperature parameter:

(15) $$\frac{dU_{oc}}{dT} = \frac{V_T}{T} \cdot ln(\frac{I_{ph}}{I_o}) + V_T \cdot \frac{d\, ln(\frac{I_{ph}}{I_0})}{dT}$$

Fig.2. Photovoltaic modules used in current - voltage measurements

Test stand and objects of research

To verify the results of computer simulation of current – voltage characteristics of analized photovoltaic modules, based on the relationship describing two - diode solar cell (Fig.1), measurements were carried out in real conditions on a stand described in [1] with radiation power density changing from 552 W/m^2 to 927 W/m^2. The objects of research were silicon modules made in monocrystalline and polycrystalline technology Sunset, Lorentz and Suntech production, shown in figure 2. The measurements of radiation power density and temperature were carried out with HT 204 and DT - 8833 meters.

Algorithm and calculation program

Based on mathematical considerations an algorithm was developed and computer simulation was carried out for selected silicon modules made in monocrystalline and polycrystalline technology. Selected parameters of used modules are shown in table 1.

Table 1 presents parameters of mono - and polycrystalline Suntech STP020 modules in standard test conditions.

Tab.1. Selected electrical parameters of Suntech STP020 module

Parameter	Polycrystalline module	Monocrystalline module
Short circuit current [A]	1,26	1,26
Open circuit voltage [V]	21,6	21,6
Temperature coefficient [%/K]	0,055	0,055
Solar cell temperature [K]	303	314
STC temperature [K]	298	298
Elementary charge [C]	$1,602 \cdot 10^{-19}$	$1,602 \cdot 10^{-19}$
Energy potential [V]	0,6	0,6
Series cells [-]	18	18
Parallel strings [-]	2	2
Diode 1 quality factor [-]	1,34	1,083
Diode 2 quality factor [-]	1,14	1,2
Boltzmann constant [J/K]	$1,381 \cdot 10^{-23}$	$1,381 \cdot 10^{-23}$
Series resistance [Ω]	1,18	1,17
MPP voltage [V]	17,6	17,6
MPP current [A]	1,14	1,14
Module area [m^2]	0,1530	0,1586

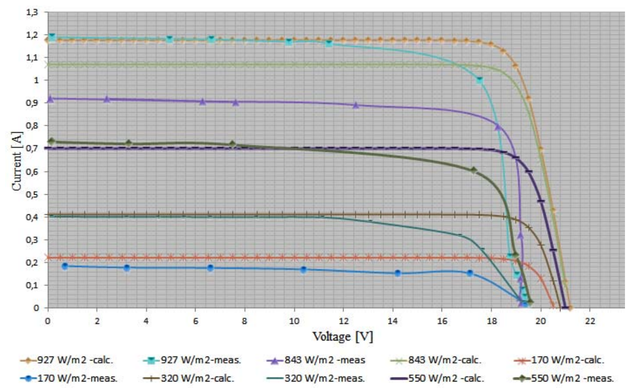

Fig.3. Current - voltage characteristics of monocrystalline module based on measurements and simulation

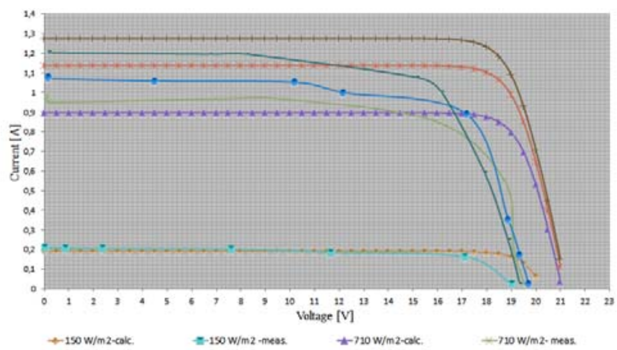

Fig.4. Current - voltage characteristics of polycrystalline module based on measurements and simulation

Results of simulation and measurements

Figure 3 shows results obtained from measurements of current – voltage characteristics of Suntech STP020 monocrystalline module in different insolation conditions and from computer simulation. Figure 4 compares results for polycrystalline Suntech STP020 module.

Figure 5 shows results obtained from measurements of power – voltage characteristics of Suntech STP020 monocrystalline module in different insolation conditions and from computer simulation. Figure 6 compares results for polycrystalline Suntech STP020 module.

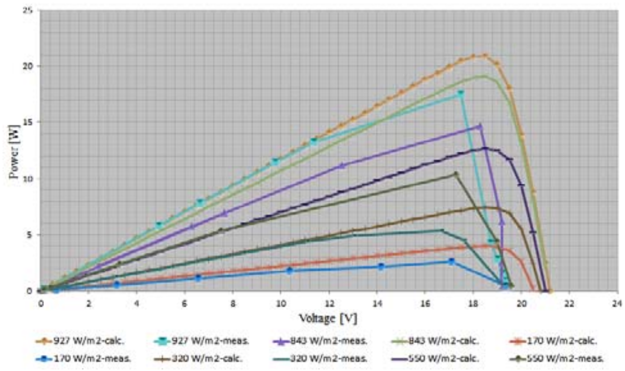

Fig.5. Power - voltage characteristics of monocrystalline module based on measurements and simulation

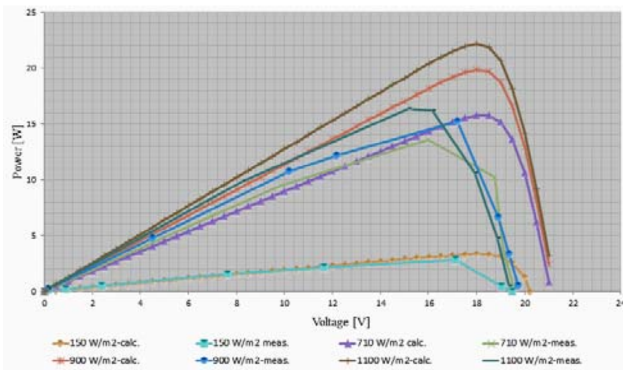

Fig.6. Power - voltage characteristics of polycrystalline module based on measurements and simulation

Conclusion

1. Analytical and experimental study of current – voltage characteristics of solar cells (modules) confirmed the usefulness of application of two - diode solar cell equivalent circuit.
2. It was found that, in each case, there is a high convergence between measured characteristics in real conditions and characteristics determined analytically on the basis of two - diode solar cell circuit, for identical insolation conditions.
3. There is a high impact of radiation power density on short - circuit current I_{sc} and low on open circuit voltage U_{oc}. The temperature increases current value about 0,07 %, in case of voltage, decreases the value about 0,4 % for each K, so the electrical power decreases [9,10].
4. Figure 3 and figure 4 show differences in open circuit voltage for proper current - voltage characteristics, where values for measurements are lower. That situation occurs both for monocrystalline and polycrystalline modules for different values of radiation power density. In case of Suntech STP020 monocrystalline module differences equals 3,4 %, while for polycrystalline cells - approximately 7 % of calculated value.
5. The reason of decrease of open circuit voltage may be a presence of parallel resistance in real solar cell (representing the way of current flow along the edge of the cell, grain boundaries or microscopic metallic connections between the grain boundaries or structural defects). They provide additional shunts.
6. The effect of the temperature on the surface of cells can cause the existing differences between the open circuit voltage for calculations and measurements [11]. The measurements of the temperature were made before determining current - voltage characteristics.
7. According to obtained results, there is a displacement of MPP for measurements towards lower values of voltage. For monocrystalline module, for radiation power density equal to 927 W/m^2 maximum power equals 20,88 W for calculations and 17,5 W for measurements. For polycrystalline module, for radiation power density equal to 710 W/m^2 respectively 15,72 W for the calculations and 13,6 W for measurements.

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***Authors**: Grażyna Frydrychowicz-Jastrzębska, PhD Eng. Poznań University of Technology, Artur Bugała, MSc Eng. Poznań University of Technology, Institute of Electrical Engineering and Electronics, ul. Piotrowo 3a, 60-965 Poznań,*
E-mail: grazyna.jastrzebska@put.poznan.pl; artur.bugala@put.poznan.pl