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The use of the MATLAB & SIMULINK environment to simulate the operation of a PV panel with an actual input function

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The paper presents a method of modelling photovoltaic (PV) cells in the MATLAB & SIMULINK environment. A two-diode photovoltaic cell structure was developed, featuring series resistance. Measurements of a PV panel were carried out to determine the value of series resistance, open circuit voltage, and short-circuit current. The model suggested was used to operate the ST-STP020S-12/Cb panel with an actual input function (measurements of solar radiation power density of the south-east area of Poland in 2011). Simulation experiments were conducted of the system modelled to determine current changes, power changes, electric energy production, voltage-current characteristics, and to come up with results and draw final conclusions.

KEYWORDS: photovoltaic cell, modelling PV panels, MATLAB environment

1. Introduction

In the recent years, research has been progressing dynamically into technical installations used to convert solar radiation energy into electric energy. This is attributable to environmental issues (Kyoto Protocol, EU white and Green papers), exhaustible fossil fuels, and a growing demand for electric energy. A very large energy potential of the Sun (the total solar energy emitted into the space is $3.816 \cdot 10^{26}$ W [14]), the accessibility of the source and the technical progress in the production of photovoltaic cells made the installed power increase from 40 GWp to 100 GWp in the years 2010-2012 [14]. Despite a little share of the systems in the global production of electric energy (wind and solar sources provide approximately 1% of the global electric energy production), photovoltaic systems are especially noteworthy because they are predicted to develop dynamically as soon as 2030-2050 and be used as a considerable number of commercial power industry systems of a large power [14].

An average solar radiation power density that reaches the upper limit of the earth's atmosphere is 1367 W/m^2 (solar constant), but the energy value on the earth is reduced by the electromagnetic radiation being absorbed and scattered in various atmospheric layers. The amount of energy thus absorbed by the biosphere is more than 10 000 times larger than the actual energy demand of all people [8]. It would seem that processing solar energy radiation may become one of the major methods of acquiring electric energy in certain geographic locations. However, this requires improved efficiency of photovoltaic conversion, lowered costs of producing photovoltaic cells, and effective methods of storing energy 0. Hence, all research in the field of electrical engineering is of crucial importance, whether related to production technologies, or to modelling, or to the simulation of PV panel operation with actual input functions.

Basic parameters that define in quantitative terms solar radiation energy emitted to the surface of the earth include radiation power density (irradiance, radiation intensity) G_r (W/m^2), sunlight (annual number of hours with the Sun's disk completely visible – it is assumed that radiation power density is then $\geq$ 200 W/m^2), and insolation (irradiation) specifying the amount of solar radiation energy reaching 1 m^2 of the earth's surface within a defined period of time (for example a year), as expressed in kWh/m^2 or J/m^2.

The amount of electric energy generated by a PV panel is a function of many factors, the most important being the power of a panel, solar energy power density, and the temperature of a photovoltaic cell. Panels operate under the changing conditions of these parameters. Within a defined period of time, irradiance is affected by both the stochastic component (current weather conditions) and by the deterministic component (time of the year and time of the day). Radiation power density changes lie within a specified range for a given geographical location and the time of the year. In Poland, irradiance is at a level of approximately up to 1000 W/m^2, but in practice its momentary values may exceed the solar constant during few short periods of the year. This is the case when a lot of Cu or Cb convective clouds accumulate (more than 60% - 70%) and momentarily do not obscure the Sun's disk. Then, the direct component of a value of even more than 900 W/m^2 is summed up with the scattering component of a value of approximately 500 W/m^2 [8].

On average, in the temperate climate sunlight lasts 1600 hours a year, but there are locations in Poland where this value is larger or smaller. Yearly, insolation in Poland ranges from 950 kWh/m^2 (south-west part of the country) to 1081 kWh/m^2 (eastern part of the country) [8]. As regards a typical load profile of electric energy consumers, a considerable disadvantage of the distribution of radiation in time in Poland is that a majority (80%) of energy accumulates in the spring and summer period, from April to June. This coincides with a period of the least demand for electric energy.

2. Electric models of photovoltaic cells

For many years, simulation research has been commonly carried out as a stage of designing technical systems. Giving an opportunity to quickly create variants of their structures and properties (modern computer systems, software packages, such as CAD/CAE), such systems reduce global costs of implementation. This also applies to the systems of renewable sources of electrical engineering, including photovoltaic ones. As for PV systems, it is important to determine the form of a mathematical model and the electrical diagram of a substitute photovoltaic panel consisting of photovoltaic cells connected in a particular way 0. Combining the modelling of converters and of other system elements with the knowledge of the distribution of radiation power density G_r in time makes it possible to simulate the operation of a system before it is assembled and to determine many parameters, including very important economy factors of an investment [9].

A single photovoltaic cell may be modelled by means of a few methods, basically differing in the approach to the properties of the p-n connection, the material used, the way of connecting the photovoltaic cell with outer systems, and the like. In the case of a single diode model (**SDM)** output current of a single cell I is defined by the following formula:

$$\mathrm{I} = \mathrm{I_{ph}} - I_{s1} \cdot \left[e^{\frac{(U+I\cdot R_S)}{\left(N_1 \cdot \frac{k\cdot T}{q}\right)}} - 1 \right] \tag{1}$$

where: I_{ph} – generated solar current:

$$\mathrm{I_{ph}} = \mathrm{I_{ph0}} \cdot \frac{G_r}{G_{r0}} \tag{2}$$

I_{ph0} – solar current generated with a radiation power density G_{r0} (most often 1000 W/m^2) [A]; G_r – actual solar radiation power density (irradiance) falling on the surface of the photovoltaic cell [W/m^2], I_{s1} – diode dark saturation current [A], k – Boltzmann constant, T – temperature of the device [°C], q – electron elementary charge, N_1 – diode quality (emission) factor N_1 = <1 ÷ 2>, U – photovoltaic cell terminal voltage [V], R_s – series resistance [Ω].

Figure 1 presents an electrical diagram of the 1-diode photovoltaic cell model designed in the SIMULNIK simulation environment.

The diode dark saturation current I_{s1} represents the value of a current generated by the p-n photovoltaic cell connection without solar radiation (G_r = 0). Again, the series resistance R_s models the resistance of the metal contacts and the metal-semiconductor transition The parallel resistance R_p defines a leakage current between the electrode grid at both sides of the connection. Its value depends on the possible flaws of the p and n semiconductor area structure, mechanical leakiness, scratches, and contamination. In the model described (diagram in Figure 1), it is assumed that the parallel resistance (shunt resistance) R_p = ∞. Literature also describes different versions of the 1-diode model: ones without the series resistance $R_s = 0$ and with a parallel resistance $R_p < \infty$ [2, 4, 6, 7, 10, 11, 13, 15].

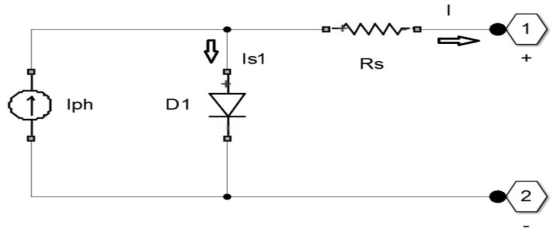

Fig. 1. SDM (1-diode) model of the photovoltaic cell in the MATLAB & SIMULINK environment

A more complex and at the same time more accurate photovoltaic cell model is a double diode model (**DDM**), where a dark saturation current is broken up into two components: diffusion one and recombination one [5]. Both components are taken into account with different weights, and the output current for the model defined in this way is specified by the following relation:

$$\mathrm{I} = \mathrm{I_{ph}} - I_{s1} \cdot \left[e^{\frac{(U + I \cdot R_S)}{\left(N_1 \cdot \frac{k \cdot T}{q}\right)}} - 1 \right] - I_{s2} \cdot \left[e^{\frac{(U + I \cdot R_S)}{\left(N_2 \cdot \frac{k \cdot T}{q}\right)}} - 1 \right] - \frac{(U + I \cdot R_S)}{R_P} \tag{3}$$

where: I_{s2} – the second diode saturation current [A]; N_1, N_2 – quality (emission) factors for the first and second diode respectively ($N_1 = 1$, $N_2 = 2$), R_p – parallel resistance [Ω].

Figure 2 presents an electrical diagram of the 2-diode photovoltaic cell model designed in the SIMULNIK simulation environment 2.

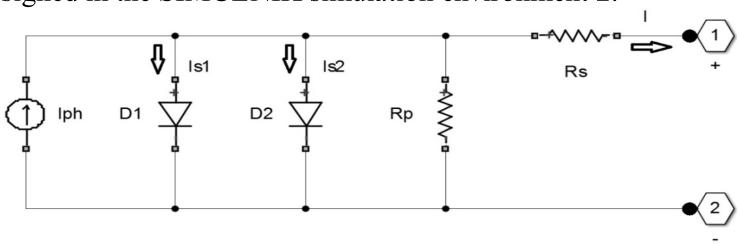

Fig. 2. SDM (2-diode) model of the photovoltaic cell in the MATLAB & SIMULINK environment

Literature also describes 2-diode models without the series resistance R_s, and with the parallel resistance R_p [1].

The series resistance values of a single photovoltaic cell are not large, amounting to a few dozen or a few hundred mΩ. As a result, the resistance R_s is usually a few ohms, depending on the manner of connecting the photovoltaic cells of the PV panel.

3. PV panel model in the MATLAB environment

In order to model a photovoltaic panel, the MATLAB environment was used, version R2014a. The model was developed using basic elements of the *Simulink* graphic environment, the *SimElectronics* and *Simscape* libraries, as well as programming elements. In this model, the fundamental element is the *Solar Cell* block, which represents a 2-diode photovoltaic cell model, relation 3, Figure 2. The *Solar Cell* block may operate in one of three variants: an 8-parameter variant or in two 5-parameter ones.

In the 5-parameter models, simplifying assumptions were adopted: a saturation current of the second diode is equal to zero ($I_{s2} = 0$), and the parallel resistance is equal to infinity ($R_p = \infty$). Additionally, the 5-parameter variant allows the block to be parametrised in relation to the short circuit current I_{SC} and the open-circuit voltage U_{OC} or a dark saturation current of the I_{S1} diode. In the case of the 8-parameter model, both components are taken into account of the dark saturation current I_{s1} and I_{s2}. A parameter set configuration is available for those versions, related to the value changes of a current generated by the photovoltaic cell I_{ph}, saturation currents I_{s1} and $I_{s2,}$ and series resistance R_s and parallel resistance R_p as a function of temperature T. Table 1 presents details of the parameters of the definition of the photovoltaic cell model variants.

Table 1. Parameters of the available photovoltaic cell models defined in the *Solar Cell* block of the *Simulink* graphic environment [5]

No.	Parameter	Model		
		5-parameter (variant 1)	**5-parameter (variant 2)**	**8-parameter**
1	Short-circuit current I_{sc} [A]	+	–	–
2	Diode saturation current D_1 I_{s1} [A]	–	+	+
3	Diode saturation current D_2 I_{s2} [A]	–	–	+
4	Generated solar current I_{ph0} [A]	–	+	+
5	Photovoltaic cell open circuit voltage U_{oc} [V]	+	–	–
6	Reference irradiance I_{r0} [W/m^2]	+	+	+
7	Diode quality factor D_1 N_1 [-]	+	+	+
8	Diode quality factor D_2 N_2 [-]	–	–	+
9	Series resistance R_s [Ω]	+	+	+
10	Parallel resistance R_p [Ω]	–	–	+

Designed in the Simulink environment, the PV panel model uses variant 1 (5-parameter one) of a series resistance $R_s > 0$. The choice of the model version is based on the largest level of conformity of its parameters with typical catalogue data of photovoltaic panels.

The structure diagram includes blocks of stimulating and modelling a panel load, required measurement systems (*Current Sensor* block), elements of determining, converting and calculating initial parameters (*Simulink-PS Converter*, *PS-Simulink Converter*, and *Integrator* blocks) and visualisation elements (*Display* and *Scope* blocks). To simulate the input function (changes in the solar radiation density G_r in time), the *Repeating Sequence Interpolated* block is used. Measurement data is read in from a binary file. Figure 3 presents a block diagram of the system employed in the research.

Additionally, a set of functions and scripts was developed in the MATLAB environment language for the procedures of determining changes in the generated current *I*, voltage *U* and power *P* of the panel terminals, and the generated electric energy as a time function for the input function $G_r(t)$ preset.

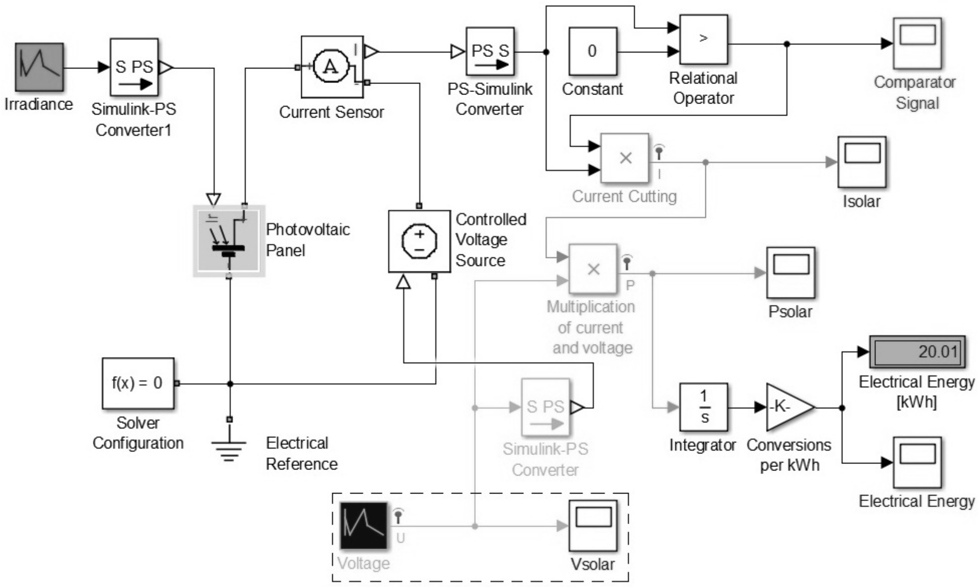

Fig. 3. Diagram of the photovoltaic panel with a voltage control system, and measurement, calculation and visualisation blocks created in the MATLAB&SIMULINK environment

The load of the panel was modelled using a controlled voltage source. A uniform distribution of radiation power density was assumed for the surface of the whole panel. The controller system to establish operating conditions for the panel at the maximum power point (*MPP)* of a respective characteristic (G_r = *const*) was simulated as a voltage source of values corresponding to the actual irradiance. For such purposes, right before the calculation block was started, a characteristic family was determined $P = f(U)$ with $G_r = const$, for G_r = <50;1500> W/m^2, with a step 50 of W/m^2. Maximum power points of successive characteristics were used to obtain a curve $U_{MPP} = f(G_r)$ to read current voltages. The set of pairs of points obtained (radiation power density and maximum power voltage U_{MPP}) was used to approximate a voltage function in relation to the radiation power density. To do so, east-squares approximation was implemented in the MATLAB environment. This made it possible to determine a maximum power point for any radiation density with satisfactory accuracy.

4. Experimental determination of I = F(U) parameters and characteristics of a PV panel

In the simulation experiments, the ST-STP020S-12/Cb panel by Suntech was used, characterised by the technical data contained in Table 2.

Table 2. Technical data of the ST-STP020S-12/Cb panel [12]

No.	Parameter name	Symbol and unit	Value
1	Rated power	P_n [Wp]	20.00
2	Open circuit voltage	U_{oc} [V]	21.60
3	Short-circuit current	I_{sc} [A]	1.26
4	Maximum power (STC)	P_{max} [Wp]	20.00
5	Current at the MPP point	I_{mp} [A]	1.14
6	Voltage at the MPP point	U_{mp} [V]	17.60
7	Operating temperature	T_o [°C]	-40 ÷ 85

The PV ST-STP020S-12/Cb panel was constructed out of 36 photovoltaic cells connected in series. In order to determine its series resistance R_s, voltage-current characteristic measurements were carried out for the radiation power density values 700 W/m^2 and 800 W/m^2, Figure 4. Points show results obtained from the measurements, full and broken lines the characteristics approximated by splines, and full (grey) line the characteristics obtained from the simulations. Due to the measurement conditions (natural light) and related temperature changes of the panel in time (from 30°C to 55°C), the characteristics are shifted in relation to those of the technical documentation of the panel for the STC standard conditions. STC. Using the characteristics and the graphic method, the panel's series resistance was determined at R_s = 2.31 Ω.

With the aid of the rated data, known panel structure, and measurements conducted, the parameters contained in Table 3 were introduced to the panel model in the MATLAB environment 4.2.

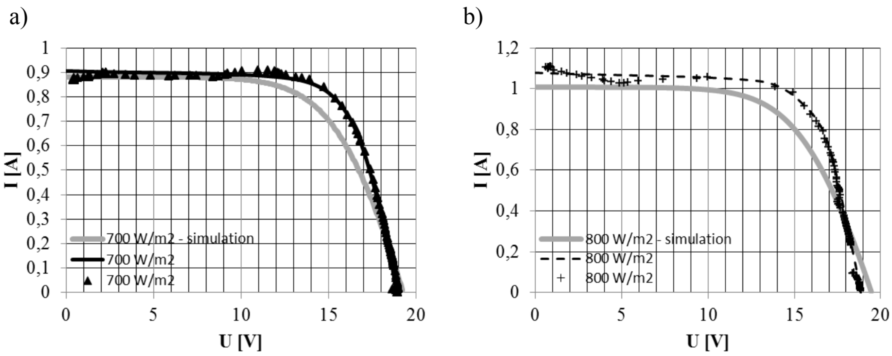

Fig. 4. Voltage-current characteristic family *I=f(U)* of the PV ST-STP020S-12/Cb panel based on the measurements, approximation, and simulation for an irradiance of a) G_r = 700 W/m^2 b) G_r = 800 W/m^2

Table 3. Parameters of the SDM model of the ST-STP020S-12/Cb PV panel (STC conditions: 1000W/m^2, 25°C, AM = 1.5)

No.	Parameter	Symbol	Value
1	Short-circuit current	I_{sc} [A]	1.26
2	Open circuit voltage	U_{oc} [V]	21.6
3	Reference irradiance	I_{r0} [W/m^2]	1000
4	Diode D_1 quality factor	N_1 [-]	1.5
5	Panel series resistance	R_s [Ω]	2.31
6	Number of cell in series	n [-]	36
7	Cell series resistance	R_s [Ω]	0.064
8	Cell energy gap	EG [eV]	1.11
9	Temperature exponent for I_s	$TXIS1$ [-]	3
10	Initial operating temperature	T [°C]	25
11	Final operating temperature	T [°C]	65

5. Operating simulation of a PV panel in the MATLAB environment with an actual input function

In order to obtain better simulation results, the panel parameters obtained from the experiment (chapter 4) were introduced to the model. As an input function in the process of simulating the operation of the ST-STP020S-12/Cb PV panel (Table 3), radiation power density measurements were used, conducted during one year (2011) by Krzysztof Markowicz, Ph.D, in the radiative transfer station in Strzyżów near Rzeszów. The measurements were carried out by means of the CM22 pyranometer from 01 January 2011 to 31 December 2012. They covered an average radiation power density and were based on a sampling interval of Δt = 36 s. To determine the solar radiation power density changes G_r of the year 2011, the operation of the panel was simulated with the actual input function. Data from a binary file was introduced to a vector of a length of 879419 measurement samples with a time step of 36 seconds. This vector was an input parameter for the *Repeating Sequence Interpolated* block.

For the purposes of this paper, an irradiance measurement result analysis was made for the above geographical location in the years 2011 and 2012 to determine sunlight as a function of a day number of the year (Figure 5), insolation as a function of a day number of the year (Figure 6), solar radiation power density changes from 1 to 10 January and 1 to 10 June of 2011 (Figure 7), solar radiation power density changes on 1 January and 1 June of 2011 (Figure 8), and monthly distribution of sunlight and an average solar radiation density (periods of $G_r > 10$ W/m^2) of 2011 and 2012 (Figure 9). Yearly electric energy production as a function of a day number of the year, seen also as energy produced on each day and energy accumulated on successive days, is presented in the form of the diagrams in Figures 10 and 11. Figures 12 and 13 show current intensity changes *I* and electric energy changes *A* on 15 January and 15 June of 2011. Figures 14 and 15 show current intensity changes *I* and electric energy changes *A* from 15 to 29 January and 15 to 29 June of 2011.

a) b)

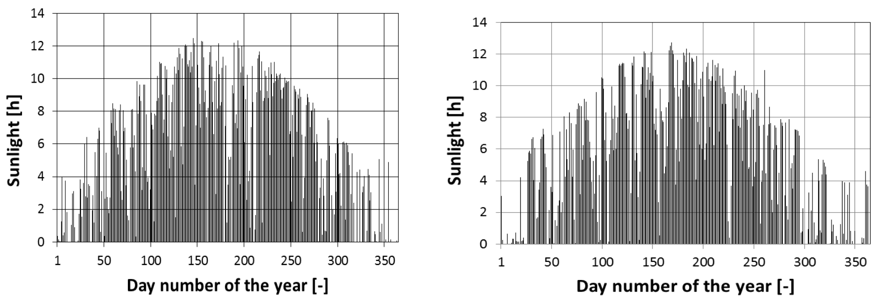

Fig. 5. Sunlight as a function of a day number of the year a) 2011 (a total of 2047 h), b) 2012 (a total of 1965 h)

a) b)

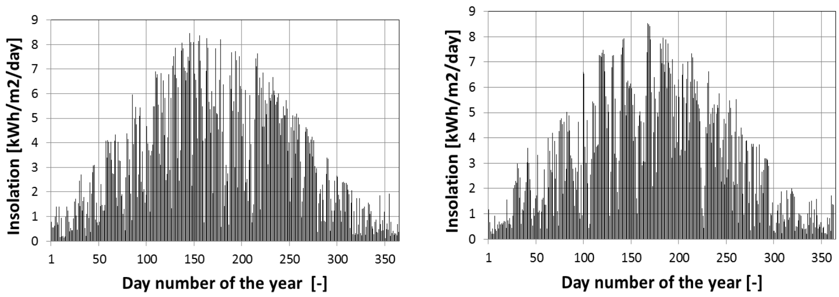

Fig. 6. Insolation as a function of a day number of the year a) 2011 (a total of 1187 kWh/m^2/year), b) 2012 (1140 kWh/m^2/year)

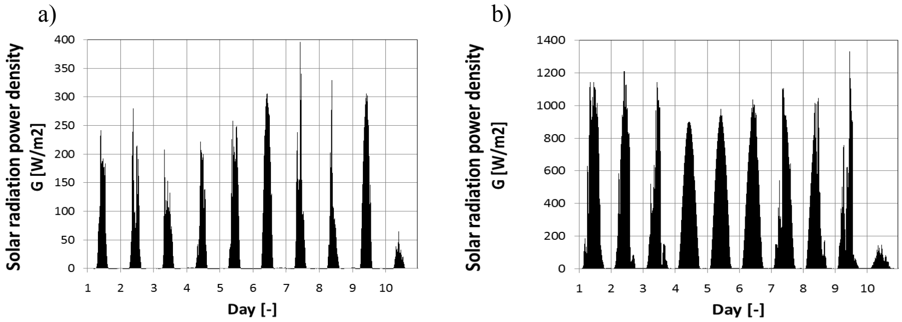

Fig. 7. Solar radiation power density changes G_r a) 1 - 10 January 2011, b) 1 - 10 June 2011

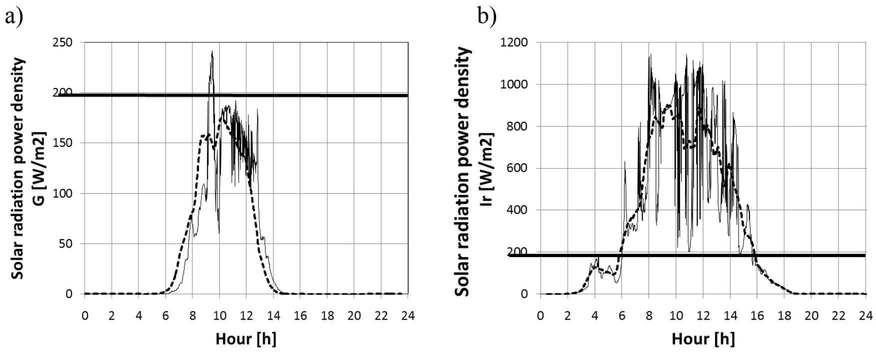

Fig. 8. Solar radiation power density changes G_r on 1 January 2011, b) 1 June 2011.

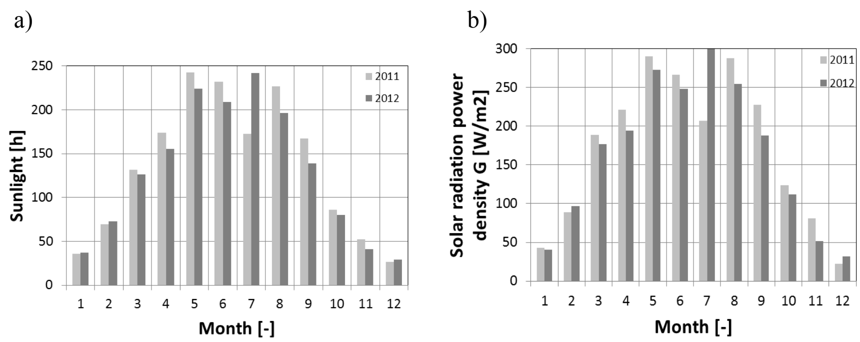

Fig. 9. Monthly distribution of a) sunlight, b) the average solar radiation power density G_r for the years 2011 and 2012

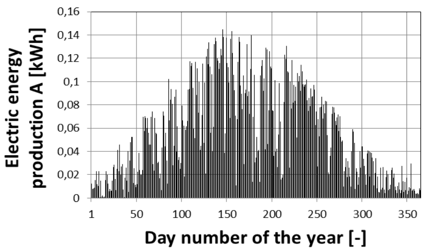

Fig. 10. Distribution of electric energy production as a function of a day number for the year 2011

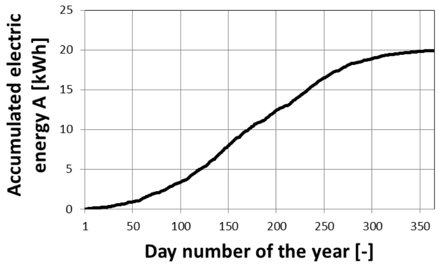

Fig. 11. Electric energy production in the year 2011 (accumulated changes)

a) b)

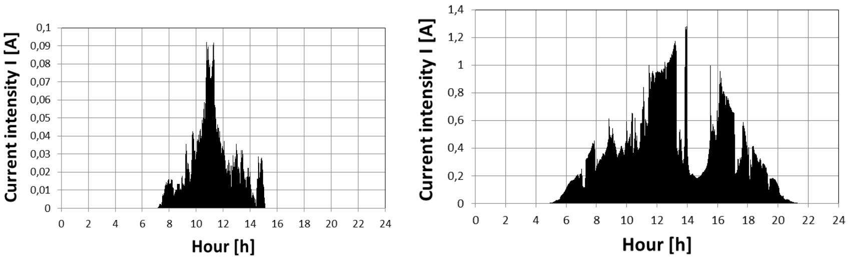

Fig. 12. Current intensity changes *I* on: 15 January 2011, b) 15 June 2011

a) b)

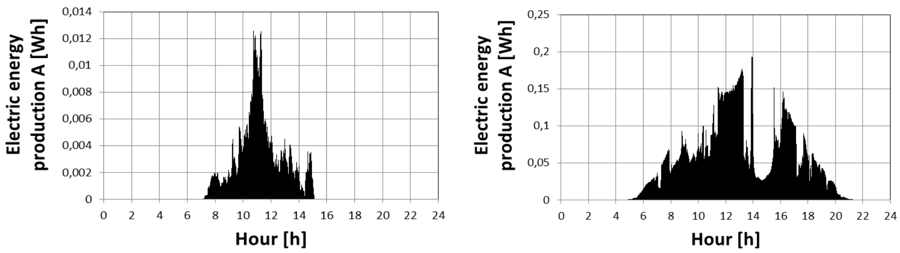

Fig. 13 Electric energy production changes *A* on: 15 January 2011, b) 15 June 2011.

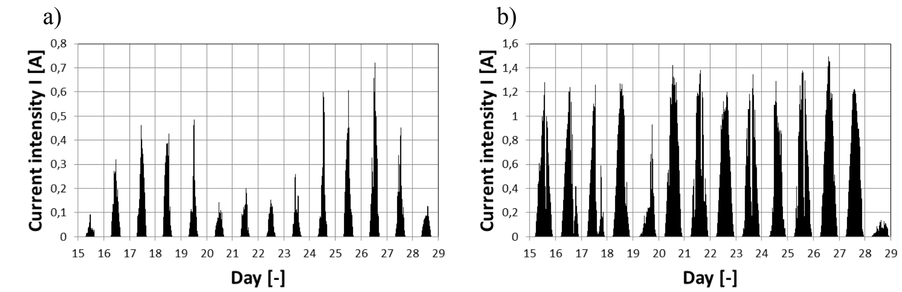

Fig. 14. Current intensity changes *I* a) 15 - 29 January 2011, b) 15 - 29 June 2011

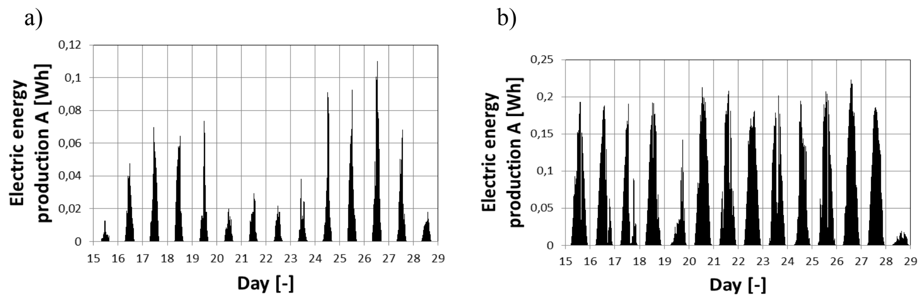

Fig. 15. Electric energy production changes *A* a) 15 - 29 January 2011, b) 15 - 29 June 2011

6. Summary

The paper presents the use of the MATLAB & SIMULINK environment to simulate the operation of the ST-STP020S-12/Cb panel with an actual input function. As was shown, the discussion confirmed the aptness of using a two-diode photovoltaic cell model with series resistance to model photovoltaic panels (PV).

Due to a considerable effect of series resistance of the panel on the output parameters (including the energy generated), this value was determined as a result of experiments. This was achieved using a graphical method requiring a voltage-current characteristic family for various values of irradiance. By comparing the voltage-current characteristics, the following conclusions can be drawn:

– in the simulation, characteristic in the part of the current source is more inclined than in the measurements. This results from the inaccuracy of the graphic method of determining series resistance,
– theoretical and obtained values of an idle voltage and short-circuit current are similar,
– in the simulation characteristic, there is a slight shift of the maximum power point to the left, thereby lowering the efficiency of the simulated system as compared to its actual capabilities,
– the divergence of characteristics at particular measurement points (Figure 4) results from the assumption that radiation intensity was evenly distributed on

the panel surface and from the changes in momentary insolation during the measurements.

With the characteristics determined, it was also possible to verify the voltage values of an open circuit and a short-circuit current.

The irradiance changes used in the simulation enabled total sunshine values to be determined at a level of 2047 h in 2011 and 1965 h in 2012 and insolation values at a level of 1187 kWh/m^2/year in 2011 and 1400 kWh/m^2/year in 2012 for the geographic location of the radiative transfer station. With the values obtained higher than the average ones that were recorded for many years in Poland (for example sunlight - 1600 h) it would seem that south-east Poland is a good location for photovoltaic systems.

On the basis of the simulation research on the modelled panel with an actual input function, it was determined that the total electric energy production was approximately 20 kWh for the data of 2011. This value includes the operation of the supervising system, whose aim was to find the panel's maximum power point and to switch it off in case of excessively low radiation power density.

Apart from irradiance, daily operation time of the PV panel affects the large difference in the average amount of energy generation. The values of the analysis of the measurement files and simulation varied respectively from 8 to 16 hours. Additionally, also the level of irradiance changed considerably in the periods of the year.

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