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QUALIMETRIC METHOD OF QUALITY ASSESSMENT OF SOLAR BATTERY PARAMETERS

© Budanov P., Kyrysov I.

Ukrainian Engineering Pedagogics Academy

Information about the authors:

Budanov Pavlo (Буданов Павло Феофанович) ORCID: http://orcid.org/0000-0002-1542-9390; e-mail: pavelfeofanovich@ukr.net, Ukrainian Engineering Pedagogics Academy, candidate of technical sciences, associate professor of Department of Electrical Engineering and Power Engineering, 16 Universitetska st., Kharkiv, 61003, Ukraine.

Kyrysov Ihor (Кирисов Ігор Геннадійович) ORCID: https://orcid.org/0000-0002-0214-8880; e-mail: kirisovuipa1980@gmail.com, Ukrainian Engineering Pedagogics Academy, Senior teacher of Department of Electrical Engineering and Power Engineering, 16 Universitetska st., Kharkiv, 61003, Ukraine.

The article investigates a qualitative method for estimating the parameters of a photovoltaic converter in a solar battery using MATLAB/Simulink circuit modeling systems. This method correlates the power parameters of solar cells with lighting, ambient temperature, and the geometric dimensions of the area of the receiving surface of the photovoltaic converter. The developed qualitative method enhances the accuracy and stability of volt-ampere and volt-watt characteristics, determining the actual output power and efficiency of the photovoltaic converter. Analytical expressions are obtained for calculating the initial parameters, considering real geometric structural changes of the surface layer of the photoelectric converter, including macro- and micro-cracks, as well as local inhomogeneities. These analytical expressions allow to calculate such parameters of the solar cell as short-circuit current, open-circuit voltage, and maximum power output, accounting for the size of the receiving surface area of the converter. A computational experiment was conducted in MATLAB/Simulink circuit modeling systems. It confirmed the influence of the geometric surface characteristics on the output parameters of the photoelectric converter, utilizing fractal geometry computation. The results of theoretical studies on the correspondence of the value of the fractal dimension to a certain value of the area, as well as the power dependence of the geometric topological surface on the value of the fractal dimension, have been confirmed. A comparison between the theoretical results and practical experiments showed a discrepancy of up to 5% in obtained data. The algorithm for building a mathematical model of a photovoltaic solar cell converter in MATLAB/Simulink circuit modeling systems, taking into account the area of the active sensing surface, was developed and presented. The proposed qualitative evaluation method is applicable for controlling the input and output parameters of the photovoltaic converter at the stage of assembly, rejection of solar modules, panels and the whole during the construction of various options of photovoltaic modules of solar power plants.

Keywords: solar cell, solar battery, photoelectric converter, qualitative surface evaluation method.

Буданов П.Ф., Кирисов І.Г. “Кваліметричний метод оцінки якості параметрів сонячних батерей”

У статті досліджується кваліметричний метод оцінки параметрів фотоелектричного перетворювача сонячної батареї за допомогою систем схемотехнічного моделювання MATLAB/Simulink, що дозволяє пов’язати параметри потужності сонячних елементів з освітленням, температурою навколишнього середовища з геометричними розмірами площі сприймаючої поверхні фотоелектричного перетворювача. Розроблений кваліметричний метод оцінки параметрів фотоелектричного перетворювача сонячної батареї, дозволяє підвищувати точність, стабільність вольт-амперної та вольт-ватної характеристик і визначити реальне значення величини вихідної потужності та ККД фотоелектричного перетворювача. Отримані аналітічні вирази, для обчислення вихідних параметрів, з врахуванням реальних геометричних структурних змін поверхневого шару фотоелектричного перетворювача, при наявності ушкоджуючих дефектів в вигляді макро- та мікротріщин и локальних неоднорідностей. Отримані аналітічні вирази, дозволяють розрахувати такі параметри сонячного елементу як струму короткого замикання, напруги холостого ходу, максимальної вихідної потужності с урахуванням величини реальної площі сприймаючої поверхні фотоелектричного перетворювача.

Проведений обчислювальний експериментом у системах схемотехнічного моделювання MATLAB/Simulink, який підтвердив вплив геометричних характеристик поверхні на вихідні параметри фотоелектричного перетворювача, на основі використання обчислювального апарата фрактальної геометрії. Підтверджені результати теоретичних досліджень, про відповідність величини фрактальної розмірності, певному значенню площі, а також про степеневу залежність геометричної топологічної поверхні від величини фрактальної розмірності.

Проведено порівняння теоретичних результатів з результатами практичного експерименту, яке показало розходження отриманих даних до 5%.

Розроблений та представлений алгоритм побудови математичної моделі фотоелектричного перетворювача сонячної батареї у системах схемотехнічного моделювання MATLAB/Simulink с врахуванням площі активної сприймаючої поверхні.

Запропонований кваліметричний метод оцінки, може бути практично використаний для контролю вхідних та вихідних параметрів фотоелектричного перетворювача на етапі збірки, відбраковування сонячних модулів, панелей і цілому при побудові різних варіантів фотоелектричних модулів сонячних електростанцій.

Ключові слова: сонячний елемент, сонячна батарея, фотоелектричний перетворювач, кваліметричний метод оцінки поверхні.

Statement of the problem

In the world, the power of solar power station increases continuously. The promising direction of increasing the energy efficiency of supply systems, raise the energy independence – it is the question of using the photovoltaic energy as in the autonomic power supply system as in the work on the system workload. In this case, the producers and distributors of solar power station refer to general equipment characteristics without taking into account more precise customization to the specific needs of the customer. The widespread use of energy equipment of the renewable energy need for a wide range of scientific research, simulation the process and complex of power energy systems, which connected with the optimization of process in the different criteria management and regulation the equipment regimes.

As a main instrument of researching the same power systems uses the method of mathematic simulation, in the result, which appears the task of creating the mathematic model, which consider the certain number of output parameters as in statistic and in dynamic regimes of function.

The main problem, that scientists and developers are facing during the creating the mathematic models of different levels and power, is the quite limited volume of information, that manufacturers of solar power plant components in electrical equipment specifications provide.

This work suggests the method of simulating the objects of solar energy by the using of simulation area MATLAB/Simulink, which allows the project manager is responsible for the selection of equipment according to the specific task. In result, it allows to increase the technical and economic indicators of function the solar power stations on the step of engineering and selection of component systems.

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Analysis of recent studies and publications

The photoelectric transmission of solar radiation on this step the technical development is the most of promising production technologies of power energy. Compare with the others technological of renewable energy, the competitive advantages are the accessibility, quite long term of function, zero mechanical loss, possibility of generating units with a wide range of capacities with the closest approximation the productive powers to the supply objects, sustainability, quiet [1-4].

To identify the characteristics and researching of behavior of the solar photovoltaic system in the different regimes of function the simulation MATLAB/Simulink – is the significant tool.

Simscape, which is the part of area Simulink, has a block of solar panels, which made an easier the process of building the model and allows to get the changing in the simulation process with the full demonstration of results [5-10].

The area of simulation MATLAB/Simulink suggests the options of ready blocks for the simulation of real physical processes. The researches use the power supply system stability modelling and analysis capabilities [11-14].

Authors in work [15-19] claim that the defining technical parameters for the evaluation of technical and economic parameters of effective the solar panels are the nominal capacity, size and term of function. The technical parameters as an idle voltage, short circuit current, current at maximum power point and others have a little effect on the economic effective and are approximately equal for all types of solar panels.

The simulation on the step of engineering allows to evaluation of parameters the solar models and give the results the initial parameters are already in the design phase, make the analysis to determine how to improve the technical and economic performance of solar power plants.

Statement of the task

Considering the relevance of the proposed issue the task of developing the model of solar photovoltaic battery in MATLAB/Simulink with the purpose of researching the connection of power parameters photo elements with the level of illumination, temperature of surrounding and geometric surface dimensions, evaluation of technical and economic parameters of system in the different regimes of function and in the specified capacity range, taking into account the thermal processes is the actual task.

Presentation of the main study.

Describing the model of photo element of solar battery

The photo element is the main element for the creating of photovoltaic module. The extended component library SimElectronics, which in the library Simscape of surrounding MATLAB /Simulink, has a block Solar Cell (fig. 1), which simulates the real photo element behavior. [1,4-6]

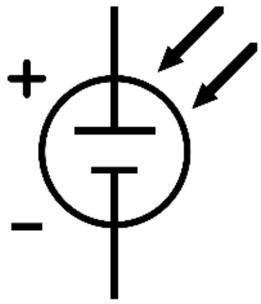

Fig 1 - Block Image Solar Cell

The model of block Solar Cell shows the photo element as a parallel combination of current sources, two exponential diodes and a parallel resistor R_p, which are connected consistently with resistance R_s (fig. 2).

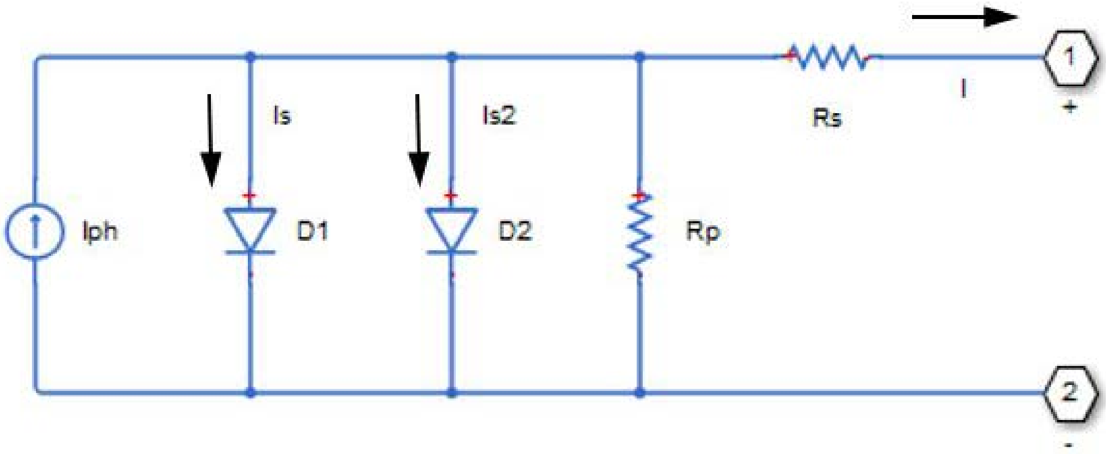

Fig. 2 - Block Equivalent Solar Cell

Photoelectric output current I, is determined by the expression:

$$I = I_{ph} - I_{s1}\left[e^{\frac{e(U+IR_s)}{N_1kT}} - 1\right] - I_{s2}\left[e^{\frac{e(U+IR_s)}{N_2kT}} - 1\right] - \frac{U+IR_s}{R_p}. \quad (1)$$

where:

$I_{ph} = I_{ph0} \cdot \frac{I_r}{I_{r0}}$ – photocurrent;

I_r – photocell illuminance (light intensity) inVt/m^2;

I_{ph0} – photocurrent, which produces during the illuminance I_{r0};

I_{s1}, I_{s2} – saturation currents of the first and second diodes respectively;

k – Boltzmann's constant;

T – temperature of photo element;

e – elementary charge;

N_1, N_2 – low intensity ratios of the first and second diodes respectively;

U – voltage on the photo element.

The block realizes the opportunity or the evaluation whole parameters of expression (1) - so-called 8-parameter model, or the evaluation only two the first coherent expressions (1) - so-called 5-parameter model, by the next assumption:

–saturation current of second diode is zero;

–resistance of parallel resistor infinitely high.

During the choosing the 5-parameter model may or uses the parameters of expression (1) $\{I_{ph0}, I_{r0}, I_{s1}, N_1, R_s\}$, or set short circuit current $I_{sc}$and no-load voltage U_{oc}, which are used the model for calculation I_{ph0} and I_{s1}.

Photoelectric force I_{ph} also is defined by the temperature of photo element. In model realized the next dependence I_{ph} from T:

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$$I_{ph}(T) = I_{ph} \cdot \left(1 + TIPH1 \cdot (T - T_{meas})\right), \quad (2)$$

where:

$TIPH1$ – temperature coefficient of first order;

T_{meas} – temperature, in which I_{ph} was measured I_{ph}.

The analysis of the existing models given above showed that the following expressions (3), (4), (5), (6) are proposed to take into account the size of the geometric surface area of the solar cell when determining the short-circuit current and voltage [1]:

$$I_N = \frac{F_o \cdot e}{h \cdot v} \cdot (1 - R) \cdot \eta \cdot K_c \cdot S_\Sigma - I_{ON}\left[\exp\left(\frac{e \cdot \left(U_V + I_N \cdot R_p\right)}{A \cdot k \cdot T}\right) - 1\right] - \frac{U_V + I_N}{R_S} \quad (3)$$

$$U_N = \left(\frac{kT}{e}\right) \cdot \ln\left(\frac{\left[\frac{F_o \cdot e}{h \cdot v} \cdot (1 - R) \cdot \eta \cdot K_c \cdot S_\Sigma \cdot\right] - I_N}{I_0} + 1\right) \quad (4)$$

where:

F_0 – is the input light flux;

e – electron charge;

h – Planck's constant;

v – frequency of the incident light flux;

R – coefficient of reflection of the light flux from the frontal surface;

η – coefficient of reflected light flux of the frontal surface;

Kc integral carrier collection coefficient;

S_G – total geometric area of the receiving surface of the semiconductor layer of the photoelectric converter.

k – Boltzmann's constant;

T – absolute temperature

A – diode coefficient (depending on the current flowing through the coefficient A can vary from 1 to 2 (diffusion or recombination currents, respectively);

R_p – series resistance;

R_S – shunt resistance.

U_V – output voltage;

$$P_{\max} = U_{oc} \cdot I_{sc} \cdot F_Z \quad (5)$$

$$\eta_{KPD} = \frac{P_{\max}}{P_p} = \frac{I_{sc} \cdot U_{oc} \cdot F_Z}{P_p} = \frac{I_m \cdot U_m}{P_p} \quad (6)$$

where:

I_m i U_m – are the values of current and voltage corresponding to the point of greatest power

η_{KPD} – efficiency factor of the photoelectric converter;

P_{max} – the maximum output power of the solar cell;

P_p – power of radiation incident on the solar cell;

I_{sc} – short-circuit current;

U_{oc} – no-load voltage;

F_Z– filling factor of the current-voltage characteristic of the photoelectric converter.

The analysis of the existing analytical expressions (3 - 6) showed that they introduce a restriction on the change in the size of the area of the receiving surface (S_G= const), which leads to the inaccuracy of constructing the volt-ampere and volt-watt characteristics.

In the work, it is proposed to model the characteristics of a solar cell taking into account the size of the area of the receiving surface, which affects the amount of output power and efficiency of the solar battery, according to expression (7)

$$S_{REAL} = S_G \cdot \alpha^{d-d_{fr}} \tag{7}$$

where:

S_{REAL} – real area of the receiving surface of the photoelectric converter, which has fractal properties;

d – topological Euclidean dimension (d_1 = 1 for a straight line, d_2 = 2 for a plane, d_2 = 3 for a volume);

d_f – fractal dimension of the surface structure of the semiconductor layer of the photoelectric converter;

α – measurement scale dimensionless coefficient that satisfies the condition α < 1.

Model for building the characteristics of panel the solar elements

To model the parameters of the solar cell, an algorithm for building a mathematical model of the surface of the semiconductor layer of the photovoltaic converter of the solar battery was developed and presented in Fig. 3 [1,7-9].

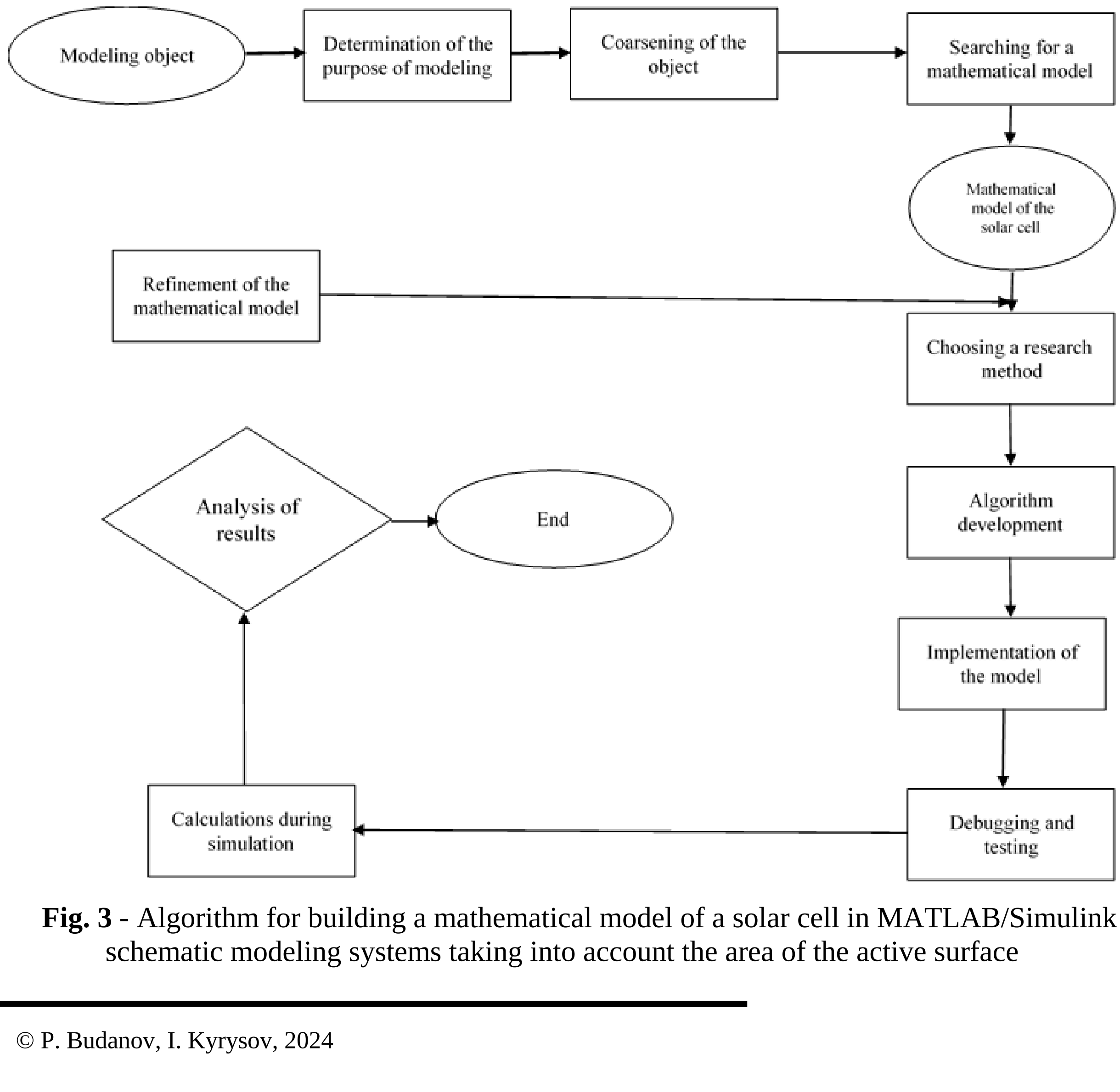

Fig. 3 - Algorithm for building a mathematical model of a solar cell in MATLAB/Simulink schematic modeling systems taking into account the area of the active surface

The values of short-circuit current, no-load voltage, maximum power and temperature coefficients, which are given in the manufacturer's passport data, were used as input parameters for the study of the solar cell.

The output parameters of the solar battery model are the maximum power, efficiency, the filling factor of the volt-ampere and volt-watt characteristics and the dependence of the output power of the solar battery on the operating voltage.

The basis for building a solar cell model is a single solar cell model.

A general mathematical description of a solar cell and a solar cell is presented, which allows to develop a simulation algorithm for a solar cell and to present the model in one of the modeling languages.

To implement the algorithm for constructing a mathematical model of a solar cell, the MATLAB/Simulink circuit modeling system computer was used [1,13-15].

For the researching the processes in solar battery and for building the characteristics in surrounding Simscape was made the model (fig. 4).

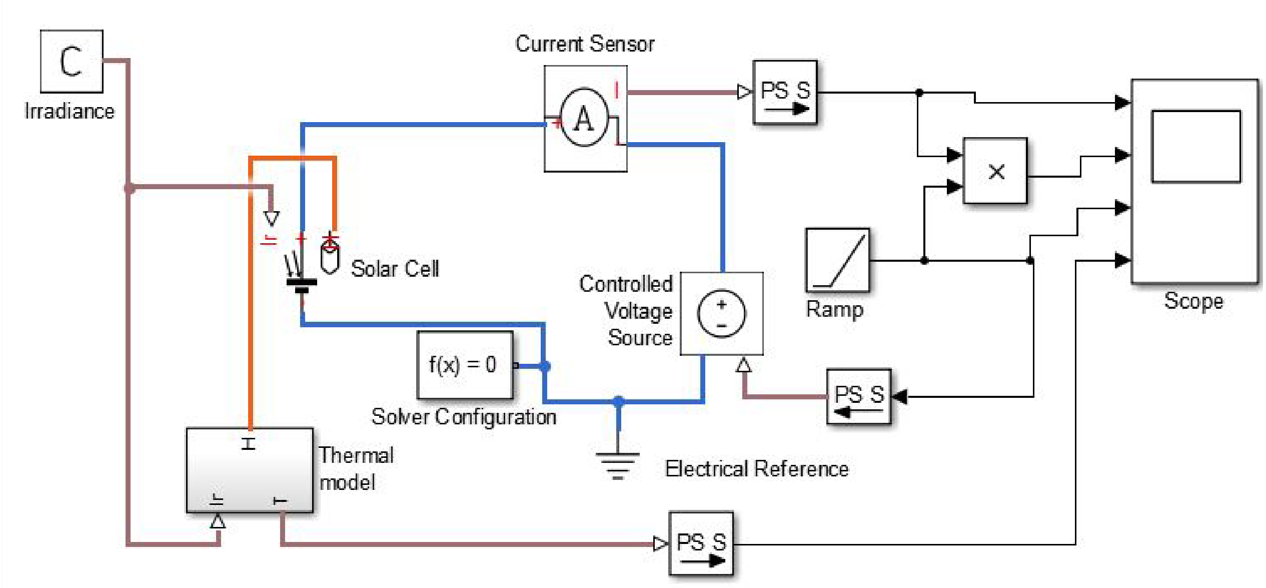

Fig. 4 - Simscape-model for researching the solar cell

The initial data for modeling were the parameters of the Axioma energy P 0.43-D solar cell, which are listed in Tab. 1

Table 1 -Characteristics of solar cell Axioma energy P 0,43-D

Electrical parameter	Parameter values
Power MPPT (Pmax)	0,43 Вт
Short-circuit current (Isc)	0.88 A
No-load voltage (Voc)	0.46 B
Current MPPT (Impp)	0,86 A
Voltage MPPT (Vmpp)	0,44 B

The intensity of the sunlight from the Irradiance unit is delivered to the port of entry «Ir» the block Solar panel and so into every photocell. Also, it enters the Thermal model unit, where a corresponding heat flow is formed, which enters the input port «H» block Solar panel.

Intensity of solar light sequentially multiplied by the area of the photocell panel and its albedo. So, the thermal flow, which comes to the solar panel and added to the interior heat of photocells, is evaluated.

The temperature of photo elements is measured by the sensor of temperature, in which the indicator comes to the block output port «T». The photo elements heats and start to give a thermal to the surrounding. This process simulates by the blocks of convective and radiation heat transfer.

The electrical terminals of the solar panel are connected by an electric circuit, which consist of the ammeter Current Sensor and ideal voltage sources Controlled Voltage Source, which is managing the input signal, that is supplied from the unit Ramp. The Ramp linear waveform change unit generates a signal in the range from 0 to the idle voltage value of the solar panel. That scheme allows to evaluate of volt-ampere characteristics of solar panel and define the maximum of electric power, producing by the panel.

The measured current value and output signal of the Ramp unit shall be supplied to the Scope oscilloscope Scope and block of signal multiplication, in which the value of power of solar panel is evaluated.

Based on the simulation results presented in Table 2, dependence graphs were constructed, which are shown in Fig. 5 (a-k).

Table 2 - Solar cell parameters for simulation using MATLAB/Simulink circuit simulation systems

Parameters	Units of measurement	Numerical values of experiments									
		№1	№2	№3	№4	№5	№6	№7	№8	№9	№10
Air temperature	К	298									
Area	m^2	0,0025	0,002499	0,002498	0,002497	0,002495	0,00249	0,002487	0,002484	0,002481	0,00248
Heat capacity of silicon	J/кg*c	840									
Energy gap	eV	1,11									
Initial temperature	*C	25									
Irradiance	W/m^2	1000									
Short circuit current I_{sc}	mA	4,850	4,710	4,629	4,625	4,548	4,548	4,536	4,136	4,125	4,06
Dimming coefficient of current-voltage characteristic Q_f	-	1,5									
Series resistance	Om	0,0047	0,0047	0,0046	0,0043	0,0042	0,0040	0,0038	0,0036	0,0036	0,0035
Thermal coefficient Teis	-	3,38									
Plate thickness	m	0,003									
Open circuit voltage V_{OC}	B	0,46	0,45	0,44	0,42	0,41	0,38	0,35	0,33	0,32	0,31

The curves in the graphs of Fig. 5 (a-k) show the dependence of the current and output power on the voltage of the solar cell. To confirm the results of the simulation of the solar cell operation process in the MATLAB/Simulink circuit modeling systems, a laboratory setup was created, which is shown in Fig. 6,7.

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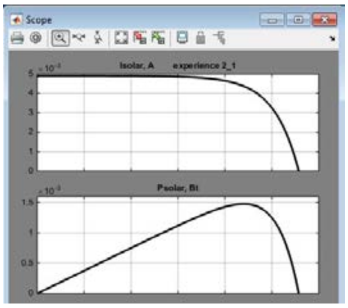
The laboratory installation includes the following devices:
1. Solar battery AB330-72P (120 photocells)
2. Ammeter
3. Voltmeter
4. Axioma energy P 0.43-D solar cell
5. Multimeter
6. Computers
7. Oscilloscope



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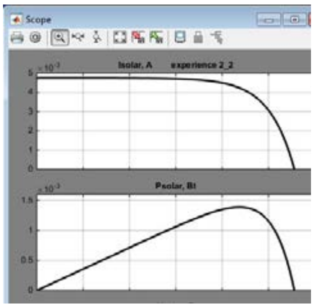

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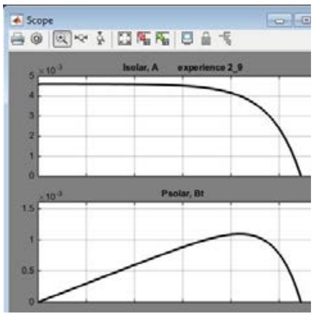

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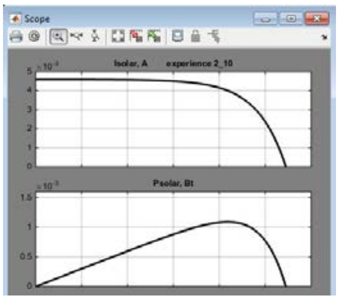

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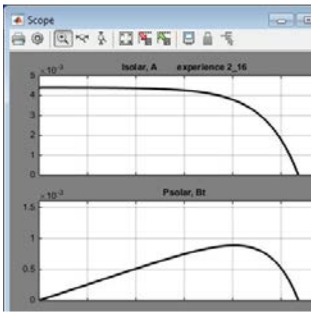

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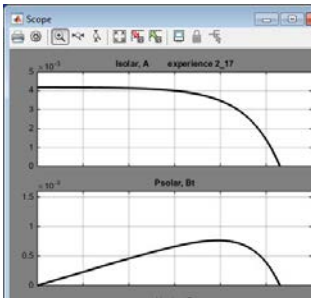

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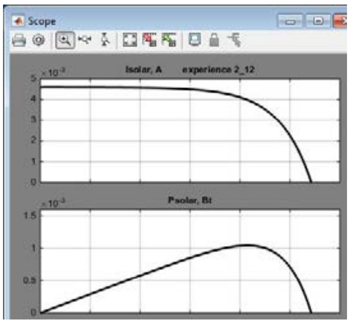

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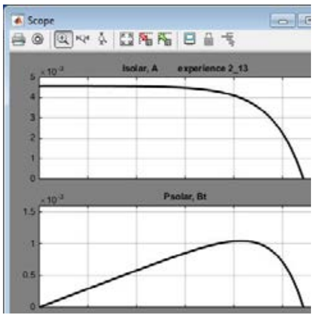

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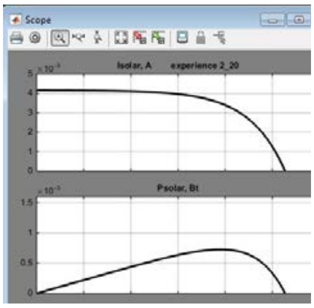

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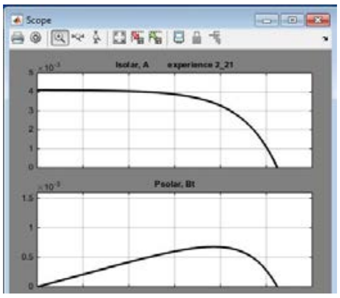

m

Fig. 5 - Graphs of the results of modeling the process of the solar cell in MATLAB/Simulink circuit modeling systems with different areas of damage to the surface of the solar cell: graphs a-k of different values of the receiving surface area according to Table 2.

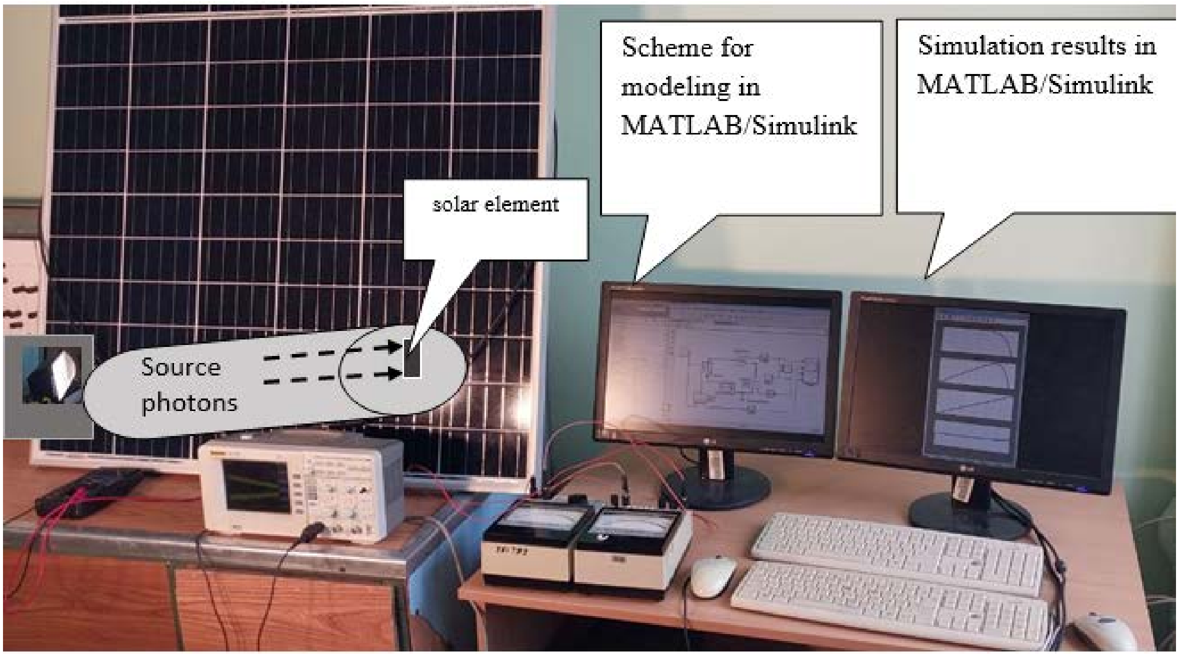

Fig. 6 - Laboratory model of an experimental setup for conducting a physical experiment on a solar cell of a solar battery

The measuring scheme of the experimental setup for conducting a physical experiment on a solar cell photoelectric converter is shown in Fig. 7

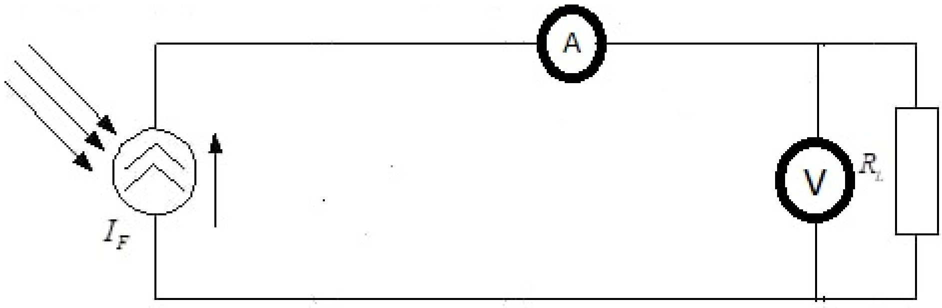

Fig. 7 - Measuring scheme of the laboratory installation

The following input parameters were selected for the experimental study of the photovoltaic converter of the solar battery: different levels of illumination and the spectral composition of incident radiation, shading of individual photocells, the coefficient of loss of incident radiation, characteristics of the semiconductor material of the solar cell and its passport parameters, operating temperature, fluxes of solar radiation, coefficient losses, which takes into account the influence of destructive factors and aging of the receiving surface of the structure of the solar cell, coefficients of dispersion of technological parameters, the solar cell of the solar panel.

The initial data for processing the primary values were the parameters of the Axioma energy P 0.43-D solar cell and the AB330-72P solar panel, which are listed in Table 1.3.

To conduct the experiment, defects in the form of scratches were artificially created on the surface of the photovoltaic converter of the solar battery, cf. Gradually increasing the area of damage to the surface of the solar cell photoelectric converter from 0.000001 m2 to 0.00001 m2, the current and voltage of the photoelectric converter were measured. The results of the experiment are presented in the table. 4

Table 3 - AB330-72P solar battery parameters

Electrical parameter	Parameter values
Maximum Power (P_{max})	330 W
Voltage at Maximum Power (V_{mpp})	37.5 V
Current at Maximum Power (I_{mpp})	8.8 A
Open Circuit Voltage (V_{oc})	45.9 V
Short Circuit Current (I_{sc})	9.12 A
Panel Efficiency	17.01 %

Table 4 - The results of the study of the parameters of the photoelectric converter of the solar battery, with different areas of damage [1]

N n\n	S_{dam}, m^2	ΔS_{dam}, m2	I, mA	U, W
1	0,0025	0	4,850	0,46
2	0,002499	0,000001	4,710	0,45
3	0,002498	0,000002	4,629	0,44
4	0,002497	0,000003	4,625	0,44
5	0,002496	0,000004	4,614	0,44
6	0,002495	0,000005	4,548	0,44
7	0,002494	0,000006	4,577	0,43
8	0,002493	0,000007	4,569	0,43
9	0,002492	0,000008	4,556	0,43
10	0,002491	0,000009	4,549	0,43
11	0,00249	0,00001	4,548	0,43

To compare the results obtained with the help of MATLAB/Simulink circuit modeling systems and experimental studies, a graph of the dependence of the area of the active surface of the solar cell photovoltaic converter on the load current and voltage was obtained.

From the graph of Fig. 8 it follows that as the value of the load current decreases, the area of the active receiving surface decreases. This can be explained by the fact that with damage to the internal structure of the semiconductor layer of the solar cell photovoltaic converter (that is, the appearance of micro- and macropores, cracks in the structure of the semiconductor layer), the internal (shunting) resistance increases, which leads to a decrease in the photocurrent and, accordingly, a decrease in the output voltage and efficiency of the photovoltaic solar cell and the entire solar cell.

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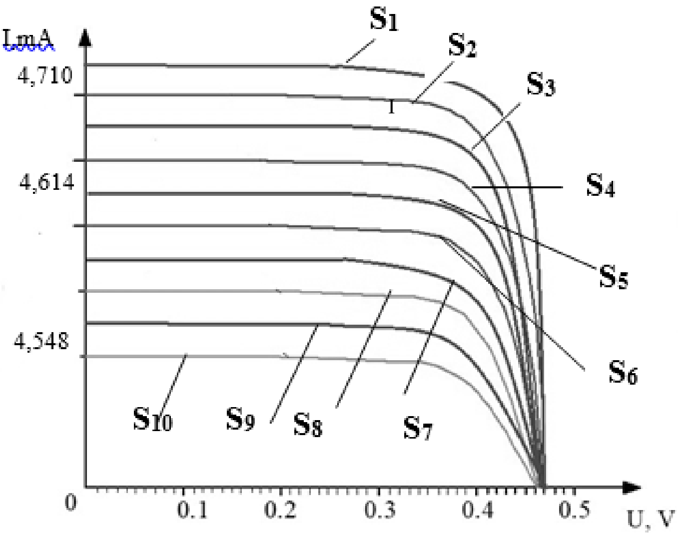


Fig. 8 - The volt-ampere characteristics of the solar cell were obtained with the help of experimental studies

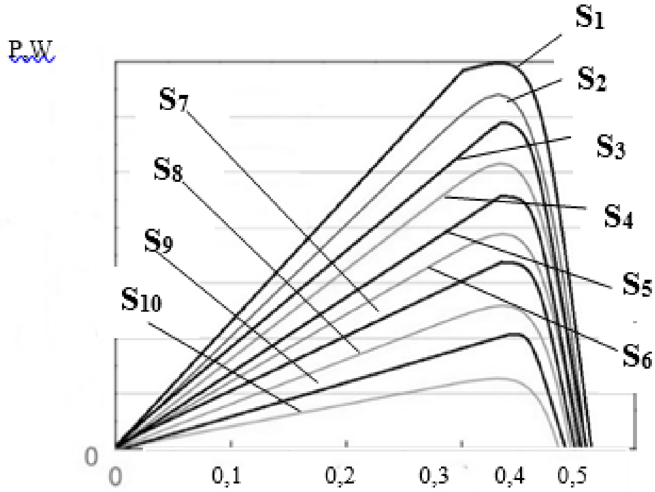
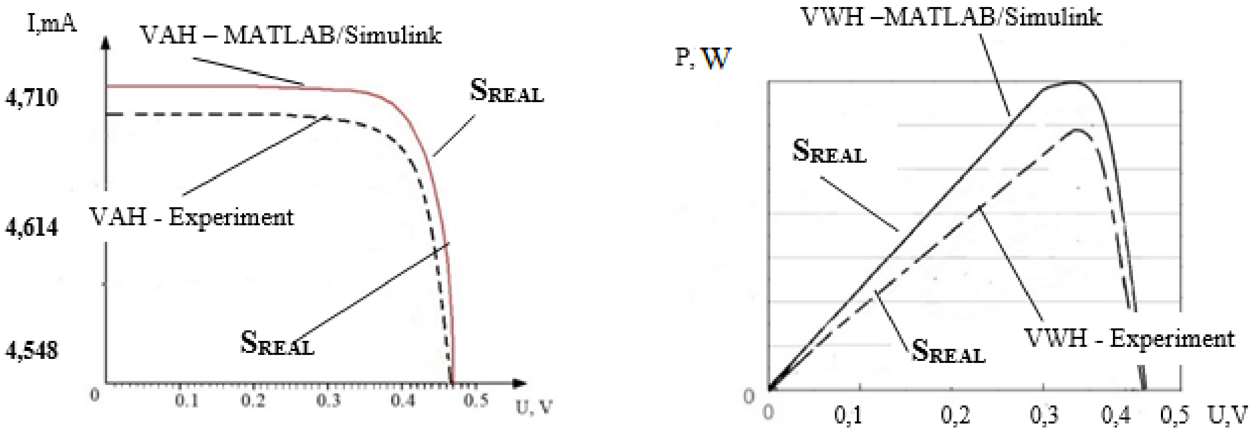


Fig. 9 - The volt-watt characteristics of the solar cell were obtained with the help of experimental studies



a) b)

Fig. 10 - Graphs of the comparison of the obtained theoretical results with the data of experimental studies: a) graph of VAH; b) graph of VWH photoelectric converter of a solar battery

Thus, in order to achieve stability and accuracy of the volt-ampere and volt-watt characteristics of the photovoltaic converter of the solar battery, it is necessary to take into account the size of the area of the active receiving surface in analytical expressions when modeling solar cells.

A comparison of theoretical and experimental data (Fig. 10) showed the adequacy of the proposed models of the solar cell taking into account the real size of the surface reproduction area, since the differences are no more than 5%.

Using the results of simulation may make a conclusion that the using Simscape-model adequately reproduces processes, which are in photo voltaic systems.

The significant possibilities of simulating the physical process, are the basis of the library Simscape, allows making a comprehensive study of photovoltaic efficiency.

Conclusions

The designed method of the evaluation the parameters of photovoltaic batteries in surrounding MATLAB/Simulink allows to connect the power parameters of photo elements with the level of lightening, the temperature of surrounding and geometrical size of surface.

Implemented the researching results simplifies the measuring of input and output parameters of the photo electrical modules for the building of solar stations and for evaluating the effectiveness of proposed solutions.

The results of simulation allow to make a conclusion that the model takes into account the main factors, which influences on the function of the solar photovoltaic panel and, in general, adequately displays the initial characteristics of the solar module.

The next researches are needed to direct to refine model parameters by the purpose to bring model results closer to real performance indicators.

As a result of the comparison of modeling and experimental data, an adequate model with a difference of no more than 5% was obtained, which is an acceptable result for modeling.

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