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A NEW METHOD FOR DETERMINING PARAMETERS OF PHOTOVOLTAIC MODULE BASED ON THE DATA FROM TECHNICAL SPECIFICATION

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In the given article the methodology of making a photovoltaic module mathematical model is presented, which lets reproduce its energy characteristics in real operating conditions. Also, the major types of mathematical models of photovoltaic converters are discussed and most well-known estimation methods of their parameters are analyzed. An original and simple way of parameters definition of photovoltaic module is introduced based on the technical specification data without using programming and developing numerical estimation algorithms. The suggested method is easily realized in the tabular program Excel with installed tool «Search for solutions». The simulation results of volt-ampere characteristic (V-I curve) of photovoltaic module Kyocera KC200GT are presented in a wide variation range of temperature and illumination. In addition, an accuracy evaluation is made by comparing the model characteristics and experimental data. The model was tested on a number of photovoltaic modules and proved good modeling results compliance with manufacturer's data. The model provides a high modeling accuracy around MPP (maximum power point). This fact allows to use it for development of effective algorithms for photovoltaic power stations controllers, circuit design advancement of converting devices, prediction of power generation, operating modes analysis and optimization for photovoltaic systems.

Keywords: photovoltaic module, solar cells, single diode model, parameters extraction photovoltaic panel.

Introduction

A rapid development of photovoltaic market creates a necessity of research connected with design, development and analysis of photovoltaic system operating modes. The main component of photovoltaic power stations is a solar panel which consists of photovoltaic modules (PM). Their operating mode modeling in real operating conditions provides a reasonable choice of main PV stations energy components, output predictions and operating mode optimization. One of the major tasks of PM mathematical modeling is authentic parameters definition which defines the modeling accuracy of the power station operating modes.

There are a lot of scientific papers and research connected with the problem of mathematical models development of photovoltaic converters. However, scientifically, the question is still unanswered. The reason of that can be the complexity and diversity of physical processes taking place in the semiconductor during solar energy conversion into electricity. Many of these processes do not correspond the physical laws and can be described only with empirical equations. One more problem is instability of main parameters of photovoltaic converters, its dependence on external climatic conditions, fabrication methods and interference on each other. For solving this problem more complicated models are introduced, special calculative algorithms, however, a «perfect» model of photovoltaic converter is not created yet.

What is remarkable, is that in many cases the tendency to increase the model accuracy leads to unjustified raise in complexity. Moreover, for many practical tasks connected with operating mode examination for photovoltaic systems it is enough to provide the reproduction of main electrical characteristics of PM with engineering accuracy. For such cases the first priorities are simplicity, universality and usability of the model.

The main goal of this paper is to develop a mathematical model of photovoltaic module according to the technical specification data given by manufacturer, which lets reproduce the module's energy characteristics considering the changes in operating conditions. The basic principles are maximal simplicity and usability for the end user. Thus, using only PM catalogue data it is possible obtain a full solar panel model of arbitrary configuration.

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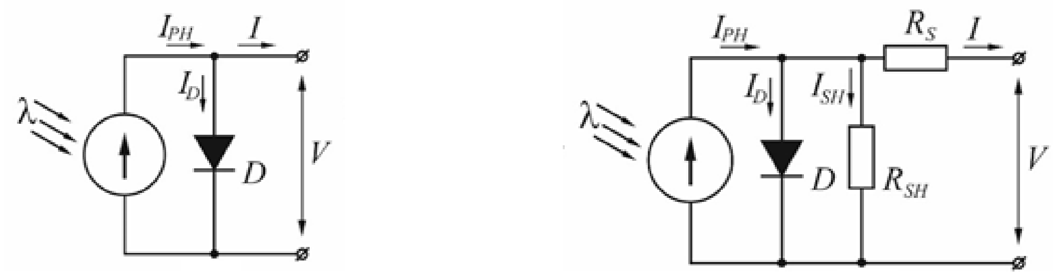
1. Solar cell model

The simplest solar cell (SC) consists of two semiconductor plates of p and n types, which generate electrical current with the influence of the sun. The working principle of SC, its construction and major physical processes are described in details in [1, 2]. The exact SC theoretical model can be obtained from equations of solid state physics, describing the rectifying effects of p-n junction [2].

The theoretical model of SC is quite cumbersome and is mainly used by photovoltaic converters developers. Simplified SC mathematical models based on the equivalent electrical circuits are widely used for analysis of the PV-systems operating modes. The idealized model of the solar cell is presented on the fig. 1, *a*.



a) b)

Fig. 1. Solar cell equivalent circuits: *a* – idealized; *b*– real with one diode

In this model the output current I and output voltage V of the solar cell are in the following relation [2]:

$$I = I_{PH} - I_D = I_{PH} - I_0 \cdot \left[\exp\left(\frac{q \cdot V}{k \cdot T} \right) - 1 \right] \tag{1}$$

The idealized model consists of the current source creating photocurrent I_{PH} and an ideal diode. The current I_D which runs through this diode is defined with the Shockley diode equation and depends on the absolute temperature *T* and SC output voltage *V* (*q*= 1.602·10-19 – electron charge; *k* =1.38·10-23J/ºK – Boltzmann's constant; I_0 – diode reverse current)

The equation (1) includes 2 undefined parameters I_{PH} and I_0 which depend on the magnitude of the solar insolation λ and SC operating temperature. With general assumptions they can be found in the form of:

$$I_{PH} = \left[I_{SC\_STC} + k_I \cdot (T - T_{STC}) \right] \cdot \lambda , \tag{2}$$

where I_{SC_STC} – short-circuit current of photovoltaic converter in standard conditions; k_I – temperature coefficient of short-circuit current; TSTC– cell temperature in standard conditions; λ –solar insolation, kW/m^2.

$$I_0 = \left[\frac{I_{SC\_STC}}{\exp\left(\frac{q \cdot V_{OC\_STC}}{A \cdot k \cdot T_{STC}} \right) - 1} \right] \cdot \left(\frac{T}{T_{STC}} \right)^3 \cdot \exp\left[\frac{q \cdot E_G}{k \cdot A} \left(\frac{1}{T_{STC}} - \frac{1}{T} \right) \right], \tag{3}$$

where E_G – band gap width of semiconductor (depends on the solar cell type).

The equations (1)-(3) let calculate the volt-ampere characteristic of the solar cell, however, the model accuracy will be not high. In real solar cells power losses are inevitable, and for the accuracy increasing the equivalent circuit on fig. 1, b is used. The volt-ampere characteristic for this model can be described as:

$$I = I_{PH} - I_D - I_{SH} = I_{PH} - I_0 \cdot \left[\exp\left(\frac{q(V + I \cdot R_S)}{A \cdot k \cdot T} \right) - 1 \right] - \frac{V + I \cdot R_S}{R_{SH}} , \tag{4}$$

where *A*– ideality factor; R_S and R_{SH} – serial and parallel solar cell resistance, accordingly.

The equation (4) includes five unknown parameters (I_{PH}, I_0, *A*, R_S, R_{SH}). To define them it is necessary to solve a complicated mathematical problem. It should be noted, that there are some more complicated SC models, e. g. models with two or three diodes in the equivalent circuit [3,4], which raise the modeling accuracy. At the same time many authors use simple models neglecting parasitic drags [5,6] or influence of a shunt resistor (R_S-model) [5,7]. This paper considers a model with one diode and two resistors (R_P-model), which is a good trade-off between simplicity and accuracy. That is why it became popular in similar studies [8-10].

2. Model of photovoltaic module

Photovoltaic module consists of many identical solar cells connected into serial-parallel circuits to increase its voltage and output power. The equation (4) for PM including N_S serial and N_P parallel solar cells transform into [5]:

$$I = N_P \cdot I_{PH} - N_P \cdot I_0 \cdot \left[\exp\left(\frac{q(V + I \cdot R_S)}{N_S \cdot A \cdot k \cdot T} \right) - 1 \right] - \frac{V + I \cdot R_S}{R_{SH}} \quad (5)$$

where *I*, *V* – current and voltage at the terminals of PM; R_S and R_{SH} – equivalent serial and shunt resistance of PM, accordingly.

The equation (5) defines the PM volt-ampere characteristic which is presented in the fig. 2.

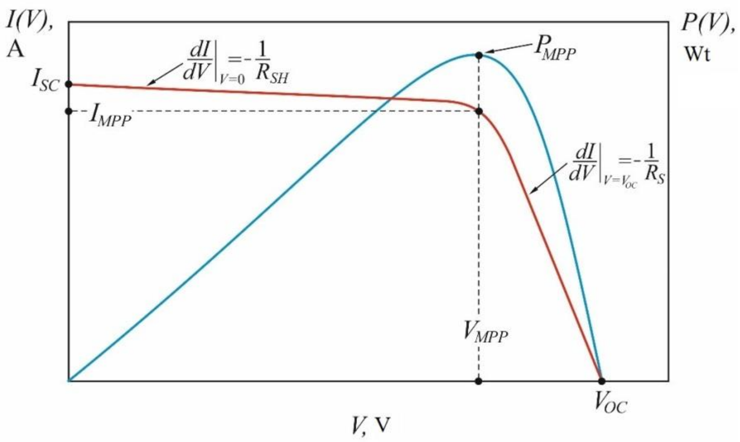


Fig.2 Volt-ampere and volt-watt characteristics of a photovoltaic module

To some extent of approximation, it can be said that the PM volt-ampere characteristic is a superposition of module's photocurrent and a dark volt-ampere characteristic of diode (unless RS>0). When the PM is irradiated, it behaves like a current source. When it is shaded, its volt-ampere characteristic is similar to the diode's one. Spectrum, intensity of solar insolation, temperature and parameters of PM depending on its type and design – all they have direct influence on the volt-ampere characteristic. Several characteristic points of the volt-ampere curve can be used for its description (fig. 2). It lets one define a number of parameters of PM equivalent circuit and evaluate the quality of the photovoltaic converter.

If make PM output terminals short-circuited, current I_{SC} will appear. Analytic form for this short-circuit current can be obtained from (6) considering *V*=0, $I = I_{SC}$ (here and below $N_P = 1$ and is not written as most PMs consist only of SCs connected in series):

$$I_{SC} = I_{PH} - I_0 \cdot \left[\exp\left(\frac{I_{SC} \cdot R_S}{A \cdot V_T} \right) - 1 \right] - \frac{I_{SC} \cdot R_S}{R_{SH}}, \quad (6)$$

where $V_T = \frac{N_S \cdot k \cdot T}{q}$ – heat stress of PM.

Short-circuit current appears because of generation and disjunction of charge carries generated by light and depends on intensity and spectrum of solar insolation, area of SC and optical properties of PM. In case of disconnected exterior circuit (*I*=0) voltage on the terminals of PM will be equal to open-circuit voltage $V=V_{OC}$:

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$$0 = I_{PH} - I_0 \cdot \left[\exp\left(\frac{V_{OC}}{A \cdot V_T} \right) - 1 \right] - \frac{V_{OC}}{R_{SH}} \quad (7)$$

Open-circuit voltage is equal to forward bias corresponding to *p-n* junction voltage change due to photocurrent, and characterizes recombination velocity in the photovoltaic converter. Open-circuit voltage mostly depends on SC saturation current.

One of the most important PM characteristics is load operation mode corresponding to maximum power point (MPP). In this case $I = I_{MPP}$, $V = V_{MPP}$ and equation (5) changes into:

$$I_{MPP} = I_{PH} - I_0 \cdot \left[\exp\left(\frac{V_{MPP} + I_{MPP} \cdot R_S}{A \cdot V_T} \right) - 1 \right] - \frac{V_{MPP} + I_{MPP} \cdot R_S}{R_{SH}} \quad (8)$$

On the volt-ampere curve MPP lets define the magnitude of fill factor (*FF*). Graphically it is equal to the maximum area of the rectangle, which can be inscribed in the volt-ampere characteristic (fig. 2):

$$FF = \frac{I_{MPP} \cdot V_{MPP}}{I_{SC} \cdot V_{OC}} \quad (9)$$

Physically fill factor defines the maximum power, which can be obtained from the photovoltaic converter and characterizes its quality. From fig. 2 it becomes clear that the numerical value of *FF* is determined by the volt-ampere curve shape which depends on the PM interior parameters: A, R_S and R_{SH}. The magnitude of R_S is defined by the SC type and geometry and depends on emitter and contact resistances. The analysis of equations (5) and (7) shows that the serial resistance does not influence on the PM characteristics in case of open-circuit. However, it defines the volt-ampere characteristic shape around the point of the open-circuit voltage. This property of R_S is often used for its direct definition by the volt-ampere characteristic inclination in the point of the open-circuit voltage.

The R_{SH} exists due to production defects of the solar cell which create alternative canals for photocurrent. Parallel resistance has significant influence on the volt-ampere characteristic shape in case of low intensity of insolation when the magnitude of the photocurrent is small. The magnitude of R_{SH} defines the volt-ampere curve inclination near the short-circuit point, thus, it is possible to estimate its numerical value. From the fig.2 it is clear that the inclination of the volt-ampere curve in the open-circuit point is bigger than in the short-circuit point. Consequently, the magnitude of R_S is much smaller than R_{SH}, and the magnitude of serial resistance has a major influence on the curve shape.

Ideality factor A determines the correlation between the volt-ampere curve of a real diode and an ideal one. Its magnitude characterizes quality of *p-n* junction and recombination type in the SC. In case of usual recombination mechanisms A=1, however, in real SCs other recombination mechanisms take place. As a consequence, for different SC types the magnitude of A can take on the value from 1 to 5, table 1 [11]. Due to the fact that A is an absolutely empirical value and it is impossible to define it from physical laws, in many cases the magnitude of ideality factor is chosen from table 1, also the assumption about absence of dependence from temperature and parasitic drags is made. This approach is valid as A has a minor influence on the V-I curve shape comparing to R_S и R_{SH}, and there are recommendations for choosing A based on numerous experiments with different PM types. For example, for silicic PMs the recommended diapason of A is 1-1.5 [9,12].

Table 1. Average values of ideality factor depending on PM production technology.

Technology	A
Si-mono	1.2
Si-poly	1.3
A-Si:H	1.8
A-Si:H tandem	3.3
A-Si:H triple	5
CdTe	1.5
CTS	1.5
AsGa	1.3

3. Parameters definition of the PM equivalent circuit

For making a worthwhile PM model it is necessary to define parameters of the equivalent circuit authentically. Due to the fact that most of the parameters depend on the module type, production technology and quality, it is rational to use technical specification data given by manufacturer for the parameters definition. However, in PM technical specification there are no parameters of the equivalent circuit given, which let one find volt-ampere characteristic directly. There are only few experimental data about electrical and thermal characteristics of photovoltaic converters, which was obtained in standard test conditions, insolation intensity λ=1000 Wt/m^2, solar spectrum AM 1.5, temperature T=25ºC. For the given PM model it is necessary to define five unknown parameters of equivalent circuit which are included in equation (6). This equation is non-linear and transcendental, so it does not have direct analytical solution. At the current moment, there are many methods of parameters definition for PM equivalent circuit which can be classified as analytical [13,14] and numerical [15,16] ones. Among numerical methods the most popular ones are evolutionary algorithms, for example, genetic algorithms [17], fish shoal [18], cuckoo [19], mine explosion [20] and many others. Detailed review of parameters definition methods can be found in [20]. Popular ones can considerably differ with assumptions, accuracy, calculation algorithm. Many methods are quite complicated and require additional mathematical knowledge and programming skills.

For making the process of PM parameters calculation easier, combined methods can be used. Some parameters (I_{PH} and I_0) are defined with analytical forms, for the rest ones (R_S, R_{SH}, A) iterative procedures are used [8,10,12]. Original combined method of PM parameters definition was suggested by M. Villalva in paper [22]. Technical specification data of PM obtained in standard test conditions (STC) is used as given data. Photocurrent and diode reverse current for STC are defined with analytical formulas:

$$I_{PH\_STC} = \frac{R_{SH} + R_S}{R_{SH}} I_{SC\_STC} . \tag{10}$$

$$I_{0\_STC} = \frac{I_{SC\_STC}}{\exp\left(\dfrac{V_{OC\_STC}}{A \cdot V_{T\_STC}}\right) - 1} . \tag{11}$$

Ideality factor A is chosen from table 1, assumed to be constant and independent from PM temperature.

Numerical values of serial R_S and parallel R_{SH} resistances are defined using iterative method, considering condition of equality of maximum power obtain experimentally $P_{MPP\_\exp}$ and as a result of calculations P_{MPP_calc} [22]:

$$P_{MPP\_\mathrm{calc}} = V_{MPP} \left\{ I_{PH} - I_0 \cdot \left[\exp\left(\frac{V_{MPP} + I_{MPP} \cdot R_S}{A \cdot V_T} \right) - 1 \right] - \frac{V_{MPP} + I_{MPP} \cdot R_S}{R_{SH}} \right\} = P_{MPP\_\exp} \tag{12}$$

For definition of parasitic drags it is necessary to perform a number of iterative calculations with different fixed values of R_S, starting from R_S=0 and after that introduce increment with definite step. The condition of iteration convergence is:

$$\left| P_{MPP\_\mathrm{calc}} - P_{MPP\_\exp} \right| < \varepsilon , \tag{13}$$

whereε – allowable error.

Minimal (initial) value of parallel resistance is set by the following expression:

$$R_{SH\_\min} = \frac{V_{MPP}}{I_{SC\_STC} - I_{MPP}} - \frac{V_{OC\_STC} - V_{MPP}}{I_{MPP}} . \tag{14}$$

The authors of this paper prove that the dependence $P_{MPP\_\mathrm{calc}}=f(R_S)$ obtained from a number of iterative calculations has explicit extremum. This fact lets one find a pair of resistances R_S and R_{SH} without complicated graphic construction. The suggested method was tested by authors on several PM models and demonstrated good correlation between calculation results and experimental ones. Simplicity and clearness made this method popular among other researchers of photovoltaic systems. This conclusion can be made from many references to this paper in scientific periodicals [5,6,8,10,13,19 and others]. Disadvantage of this method is quite complicated process of R_S and R_{SH} definition, which requires certain programming skills and competence in applied mathematical software.

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4. Suggested method of PM parameters definition

In this paper an alternative and easy way of PM parameters definition for equivalent circuit is suggested. It lets user solve this problem within minimal time providing engineering accuracy. In this method combined algorithm is used which is easily realized in tabular program Excel with installed tool «Search for solutions». The idea is the following: using chosen and fixed value of A, the condition of equality of calculated I_{MPP_calc} and experimental I_{MPP_exp} PM currents in MPP is considered.

After putting equations (10), (11) in (8) the result is:

$$\frac{R_{SH}+R_S}{R_{SH}} I_{SC\_STC} - \left[\frac{I_{SC\_STC}}{\exp\left(\frac{V_{OC\_STC}}{A \cdot V_{T\_STC}}\right) - 1} \right] \cdot \left[\exp\left(\frac{V_{MPP} + I_{MPP} \cdot R_S}{A \cdot V_{T\_STC}} \right) - 1 \right] - \frac{V_{MPP} + I_{MPP} \cdot R_S}{R_{SH}} - I_{MPP} = 0, \quad (15)$$

where $V_{T\_STC} = \frac{N_S \cdot k \cdot T_{STC}}{q}$ − heat stress of PM in STC.

Equation (15) includes only two unknown parameters and it can be considered as objective function with two variables R_S and R_{SH}. Then the procedure of PM parameters definition comes to creation of Excel list where should be a table for input of PM technical specification data and formulas (10), (11) and (15). After launching the tool «Search for solutions», it is necessary to choose a cell with formula (15) as an objective function. Cells with unknown parameters R_S and R_{SH} should be set as variables.

Upper and lower variation limits of the variables can be in diapason:

$$\begin{gathered} 0.002\frac{N_S}{N_p} \le R_S \le 0.005\frac{N_S}{N_p} \\ 1\frac{N_S}{N_p} \le R_{SH} \le 15\frac{N_S}{N_p} \end{gathered} \quad (16)$$

For getting a final result, it is not necessary to develop new programs and computational algorithms. What is necessary is to set calculation parameters in the dialog box: accuracy limits, maximum number of iterations, maximum calculation time, etc. and start the performance. An obvious advantage of the suggested method is maximum simplicity and universality. Once created calculation form can be used many times for parameters definition of different PM types.

5. Modeling of PM energy characteristics

Almost all PM parameters depend on temperature and insolation intensity. For parameters such as A, R_S and R_{SH} these dependences are less significant and can be neglected, however, for I_{PH} and I_0they should be taken into account. In this paper for finding the values of I_{PH} and I_0 in case of changing climate conditions during operation, the following equations were used [2]:

$$I_{PH} = \left[\frac{R_{SH}+R_S}{R_{SH}} I_{SC\_STC} + k_I \cdot (T - T_{STC}) \right] \cdot \frac{\lambda}{\lambda_{STC}} \quad (17)$$

$$I_0 = \frac{I_{SC\_STC} + k_I \cdot (T - T_{STC})}{\exp\left(\frac{V_{OC\_STC} + k_V \cdot (T - T_{STC})}{A \cdot V_T} \right) - 1} \quad (18)$$

Having the values of temperature and insolation for energy characteristic modelling it is necessary to solve equation (5). For its solving Newton-Raphson method was used: algorithm of finding a numerical solution of equation $f(x)$=0 yields iterative calculation procedure:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}, \quad (19)$$

where $f'(x)$ is function derivative.

Equation (6) transforms into:

$$f(I) = I_{PH} - I - I_0 \cdot \left[\exp\left(\frac{V + I \cdot R_S}{A \cdot V_T} \right) - 1 \right] - \frac{V + I \cdot R_S}{R_{SH}} = 0 \tag{20}$$

Taking into account the equation (41) gives:

$$I_{n+1} = I_n - \frac{I_{PH} - I_n - I_0 \left[\exp\left(\frac{V + I_n \cdot R_S}{A \cdot V_T} \right) - 1 \right] - \frac{V + I_n \cdot R_S}{R_{SH}}}{-1 - I_0 \cdot \frac{R_S}{A \cdot V_T} \cdot \exp\left[\frac{V + I_n \cdot R_S}{A \cdot V_T} \right] - \frac{R_S}{R_{SH}}} \tag{21}$$

Equations (17)-(21) are basic for making a PM mathematical model. This algorithm of energy characteristics calculation can be realized using MS Excel as well as other mathematical software [23, 24]. For model testing the data from technical specification of PM Kyocera KC200GT was used [25]. The modelling results were compared to experimental volt-ampere characteristics and results of other published studies [10, 12, 19, 22]. Table2 presents technical specification data of PM Kyocera KC200GT; table 3 presents calculated parameters of equivalent circuit obtained from mathematical modelling.

Table 2. Technical specification data of PM Kyocera KC200GT in standard test conditions

Technology	Si-poly
P_{MPP}	200.143 W
V_{MPP}	26.3 V
I_{MPP}	7.61 A
V_{OC}	32.9 V
I_{SC}	8.21 A
k_V	-0.123 V/ºK
K_I	0.00318 A/ºK
N_S	54
N_P	1

Table 3. Calculated parameters of equivalent circuit of PM Kyocera KC200GT

Parameter/ Method (publication)	Suggested method	Simplified analytical method (R_S-model)	Analytical method with fixed *A* (R_P-model) [10]	Combined method (R_P-model) [22]	Numerical method (R_P-model) [12]	Numerical method, evolutionary algorithm [19]
I_0, A	$9.891 \cdot 10^{-8}$	$7.712 \cdot 10^{-8}$	$9.763 \cdot 10^{-8}$	$9.825 \cdot 10^{-8}$	$4.812 \cdot 10^{-8}$	$5.12 \cdot 10^{-10}$
I_{PH}, A	8.214	8.210	8.213	8.214	8.215	8.215
A	1.3	1.283	1.3	1.3	1.235	1.017
R_S, Ohm	0.223	0.255	0.231	0.221	0.247	0.257
R_{SH}, Ohm	446.293	∞	597.386	415.405	414.89	117.922

Analysis of data from table 3 demonstrates good correlation between equivalent circuit parameters of suggested PM model and results of published studies. For testing the ability of model to display the volt-ampere curve in real operating conditions calculation of model characteristics with changing insolation and module temperature was conducted, fig. 3, 4. The curves correspond to calculated characteristics and experimental data is marked on the curves. From fig. 3 and 4 it can be seen that PM model characteristics are in a good correlation with experimental ones in a wide range of temperature and insolation. Conducted calculation experiments proved that the modelling results of the volt-ampere characteristic are identical to ones presented in papers [10,12,22]. The explanation is that all models of these studies were based on the same initial equations, and the difference is only in definition methods of the equivalent circuit parameters. Absolute error of the model in comparison to experimental data for PM Kyocera KC200GT for various insolation is shown on the fig. 5.

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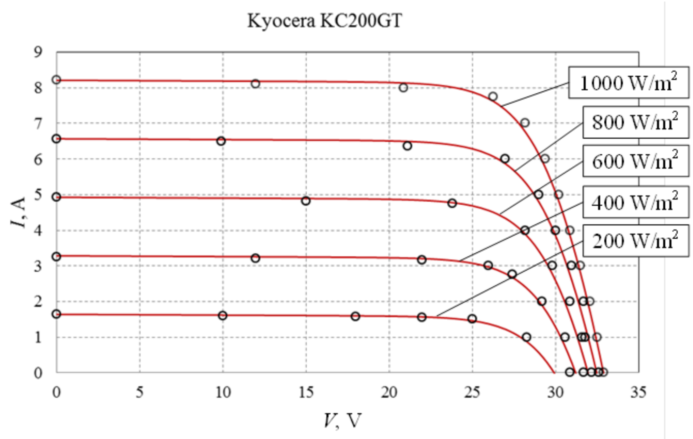

Fig.3. Calculated and experimental volt-ampere characteristics of PM Kyocera KC200GT with changing insolation (T=25 ºC).

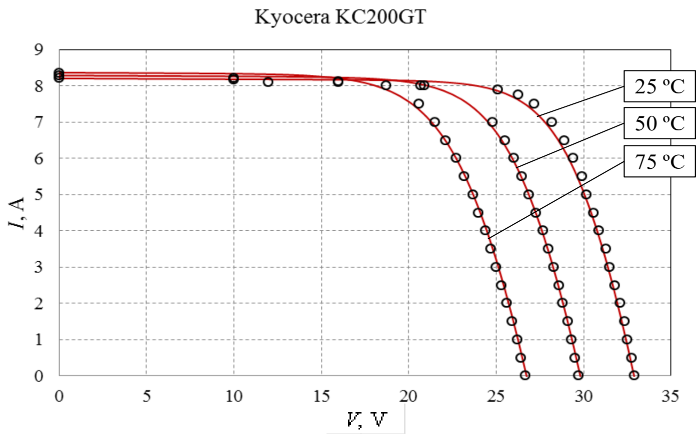

Fig.4. Calculated and experimental volt-ampere characteristics of PM Kyocera KC200GT with changing module temperature (λ=1000 W/m^2).

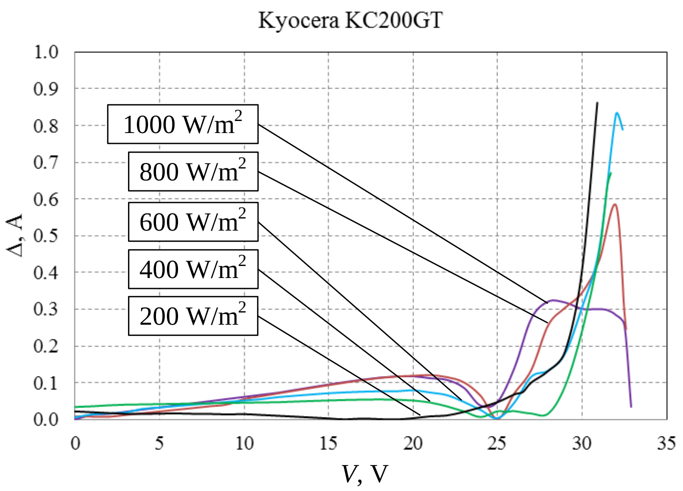

Fig.5. Absolute errors of suggested model of PM Kyocera KC200GT in case of changing insolation (T=25 ºC).

Analysis of the results shows that the magnitude of the absolute error of the model in all insolation diapason does not exceed 0.85 A. Maximal error appears in modes which are close so open-circuit operation. Due to the fact that most photovoltaic power stations work with MPPT controllers, relatively high error in these modes is no critical. It is far more important to provide high modelling accuracy in modes which are close to MPP. The suggested model demonstrates desired results. For accuracy estimation of the model, data of the PM comparison analysis from [26] was used. Regarding this analysis it can be said, that the model provides accuracy which is comparable with other known R_P-models, exceeds R_S-models in accuracy and is slightly inferior to more complicated models based on two diodes. An important advantage of the model is high accuracy of PM energy characteristics modelling in case of changing temperature. It can be provided due to the fact that for definition of diode reverse current instead of frequently used equation (3) in the suggested model a more precise analytical formula (18) is used, first suggested in paper [22].

The suggested model was tested on a number of popular photovoltaic modules of poly- and monocrystalline type and demonstrated satisfactory results: relative error for all the tested PMs around MPP does not exceed 5%.

Conclusions

In the paper results of research about enhancement of photovoltaic modules modelling are presented. Based on the conducted comparison analysis of wide spread mathematical models types of photovoltaic converters, a base structure of exponential model with one diode was chosen.

Application of given model with preliminarily chosen and fixed value of ideality factor lets noticeably simplify mathematical description of the studied object. Thus, combined method can be used for PM parameters definition, where photocurrent and diode saturation current are found with analytical expressions and for parasitic drags numerical method is used. Advantage of this approach is ability to define all unknown PM parameters using only technical specification data as initial data. And for parasitic drags definition tabular program Excel with installed tool «Search for solutions» can be used. This tool lets one easily calculate the values of serial and parallel resistances without programming and calculating algorithms. The suggested method of PM parameters definition provides high automation of calculation using universal form on the Excel list, which can be repeatedly used for parameters definition of various PMs.

The suggested model was tested on a number of photovoltaic modules and showed good correlation of modelling results with data given by maufaturer. The model provides high modelling accuracy around maximum power point. Thus, it can be used for making effective algorithms for photovoltaic power stations controllers, enhancement of circuit technology of converting devices, prediction of electrical energy generation by photovoltaic systems, analysis and optimization their operating modes.

The direction of further research is the development of a complex mathematical model of photovoltaic power plants and hybrid energy systems based on them in order to study their modes and optimize the composition of the equipment.

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