МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ФІЗИЧНИХ І ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ І ТЕХНІЧНИХ СИСТЕМ

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ANALYTICAL DETERMINATION OF THE PHOTOVOLTAIC MODULE MAXIMUM POWER POINT PARAMETERS BASED ON THE MANUFACTURER'S DATASHEET

The analytical approach to predict the maximum power point parameters of photovoltaic module at varying operating conditions such as temperature and solar irradiation level is proposed. Input data for calculations are standard module parameters from manufacturer's datasheet only. Analytical expressions for current, voltage, and power at maximum power point have been obtained via the Lambert W function. Calculation of the maximum power point electrical parameters for several photovoltaic modules realized by proposed approach shows, in general, good accuracy in maximum power point determination, which is comparable with more complicated models, except the case of thin-film modules.

Keywords: Photovoltaic module; Maximum power point; Lambert W function.

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АНАЛІТИЧНЕ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ТОЧКИ МАКСИМАЛЬНОЇ ПОТУЖНОСТІ ФОТОЕЛЕКТРИЧНИХ МОДУЛІВ НА ОСНОВІ КАТАЛОГІВ ВИРОБНИКІВ

В роботі запропоновано аналітичний підхід до визначення параметрів точки максимальної потужності фотоелектричного модуля при різних умовах експлуатації, таких як температура і інтенсивність сонячного випромінювання. Вихідними даними для розрахунків є стандартні параметри модуля, що наводяться у каталогах виробників. Аналітичні вирази для струму, напруги та потужності в точці максимальної потужності були отримані через W-функцію Ламберта. Проведений за допомогою запропонованого підходу розрахунок електричних параметрів в точці максимальної потужності для низки фотоелектричних модулів показав, в цілому, високу точність у визначенні точки максимальної потужності порівняно з використанням складніших моделей, за винятком випадку тонкоплівкових модулів.

Ключові слова: фотоелектричні модуль; точка максимальної потужності; W-функція Ламберта.

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АНАЛИТИЧЕСКОЕ ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ТОЧКИ МАКСИМАЛЬНОЙ МОЩНОСТИ ФОТОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ НА ОСНОВЕ КАТАЛОГОВ ПРОИЗВОДИТЕЛЕЙ

В работе предложен аналитический подход к определению параметров точки максимальной мощности фотоэлектрического модуля при различных условиях эксплуатации, таких как температура и интенсивность солнечного излучения. Исходными данными для расчетов являются стандартные параметры модуля, приводимые в каталогах производителей. Аналитические выражения для тока, напряжения и мощности в точке максимальной мощности были получены через W-функцию Ламберта. Проведенный с помощью предложенного подхода расчет электрических параметров в точке максимальной мощности для ряда фотоэлектрических модулей показал, в целом, хорошую точность в определении точки максимальной мощности по сравнению с использованием более сложных моделей, за исключением случая тонкопленочных модулей.

Ключевые слова: фотоэлектрические модуль; точка максимальной мощности; W-функция Ламберта.

Formulation of the problem

Mathematical modeling is one of the tools used in the design process for optimization of the technical and economic parameters of electric power supply solar systems and determination of the optimal proportion of photovoltaic power generation in hybrid systems.

The most important component of the mathematical model of a photovoltaic (PV) system is a model of PV module, which, on the one hand, should reflect PV module parameters with sufficient accuracy at variable external conditions, i.e. at different temperatures and levels of solar irradiation and, on the other hand, should not require significant amount of computations. The last requirement is especially important for long-term modeling of photovoltaic system operation and it is satisfied in the best way by analytical solution.

Analysis of last investigations and publications

In most cases, when the energy simulation of photovoltaic system is realized, PV module operation is taken at maximum power condition, assuming that maximum power point (MPP) tracker is used in the system [1-3]. PV module data from manufacturer's datasheet are taken as input.

Based on the outcomes and objectives of model of PV module the approaches to PV module modeling can be divided into three categories: (i) definition of current-voltage (I-V) characteristic equation, (ii) definition of some important points of I-V characteristic, including MPP, and (iii) definition of PV module maximum power only.

The methods of the first category, presented, for example in [4, 5], are widely used now and keep on improving. However, the main disadvantage of such methods for MPP parameters determination is the necessity of the numerical solution of the transcendental equations system that results in significant computation amount for long-term modeling of photovoltaic systems.

In [6] the exact analytical explicit expression of I-V characteristic for single-diode model of PV cell using the Lambert W function was obtained. However, in this case the solving of transcendental equations is also required to determine such MPP parameters as voltage, current, and maximum power.

Model of King [7] represents the second category. This model accurately predicts MPP parameters, but it requires some incoming parameters that are normally not available from the manufacturer's datasheets [4].

The third category is represented, for example, by the model of maximum power definition based on the determination of the fill factor dependence on temperature and solar irradiance [8]. However, the values of short circuit current, open circuit voltage and MPP current and voltage under two levels of solar irradiance and two PV module temperatures are needed to realize this model. In addition, it is not possible to determine operational values of MPP voltage and current, which are required to PV system simulation when DC-DC converter, inverter, and other components of the system are taking into account.

The purpose of the investigation

The purpose of the investigation is to develop non-iterative analytical approach to predict the MPP parameters of PV module under varying operating conditions using only standard parameters from manufacturer's datasheet as input data.

Statement of the basic material of the investigation

A single-diode model of PV cell with ideality factor A corresponds to equivalent circuit presented in Fig. 1.

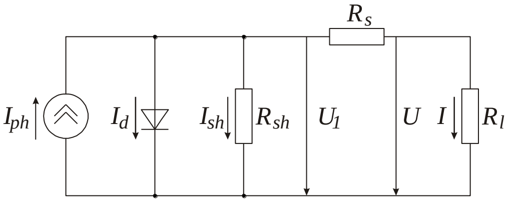

Fig. 1. The equivalent circuit of single-diode PV cell model

The load current is defined as

$$I = I_{ph} - I_d - I_{sh}$$

where I_{ph} is the photocurrent of charge carriers generated by solar irradiation;
I_d is the forward-biased p-n junction current;
I_{sh} is the shunt current of PV cell.

Last two currents are determined by the expressions:

$$I_d = I_0\left(e^{\left(\frac{U_1}{AV_t}\right)} - 1\right) = I_0 e^{\left(\frac{U_1}{AV_t}\right)} - I_0;\ I_{sh} = \frac{U_1}{R_{sh}},$$

where $V_t = kT/q_e$ is the thermal voltage;
$q_e = 1{,}6\cdot 10^{-19}$ C is the electron charge;
$k = 1{,}38\cdot 10^{-23}$ J/K is the Boltzmann's constant;
T is the absolute temperature of a PV cell;
I_0 is the reverse saturation current of the p-n junction;
U_1 is the voltage applied to the p-n junction;
R_{sh} is the shunt resistance of a PV cell.

Then

$$I = I_{ph} + I_0 - I_0 e^{\left(\frac{U_1}{AV_t}\right)} - \frac{U_1}{R_{sh}} \tag{1}$$

The load voltage can be defined as

$$U = U_1 - IR_s, \tag{2}$$

where R_s is the series resistance of a PV cell.

The MPP current will be found under condition of the maximum power transfer to the series-connected load resistance R_l and PV cell series resistance R_s. The correctness of such approach will be discussed below.

The power that is transferred to R_s and R_l is

$$P = U_1 I = \left(I_{ph} + I_0 - I_0 e^{\left(\frac{U_1}{AV_t}\right)} - \frac{U_1}{R_{sh}}\right)U_1$$

Then

$$\frac{\partial P}{\partial U_1} = I_{ph} + I_0 - I_0 e^{\left(\frac{U_1}{AV_t}\right)}\left(1 + \frac{U_1}{AV_t}\right) - \frac{2U_1}{R_{sh}}$$

If this expression is put to zero, then:

$$\frac{I_{ph} + I_0}{I_0} - 2\frac{U_{1n}}{R_{sh}I_0} = \left(1 + \frac{U_{1n}}{AV_t}\right)e^{\left(\frac{U_{1n}}{AV_t}\right)}, \tag{3}$$

where U_{1n} is the voltage applied to the p-n junction at MPP.

With the introduction of variable $z = U_{1n}/V_t A$ and multiplication of left and right hand parts by e Eq. (3) can be written as

$$e\frac{I_{ph} + I_0}{I_0} - e\frac{2V_T A}{R_{sh}I_0} = (1+z)e^{(1+z)}$$

The solution of this equation can be expressed using Lambert W function $W_0(x)$ [9]:

$$z = W_0\left(e\frac{I_{ph} + I_0}{I_0}\left[1 - \frac{2V_t Az}{R_{sh}(I_{ph} + I_0)}\right]\right) - 1. \tag{4}$$

Eq. (4) is transcendental relatively to z, and, hence, to U_{1n}. This equation can be simplified taking into account that the shunt resistance has a significant impact on the I-V characteristic of PV cell at low voltages only [10], when the diode current I_d is small, and PV cell efficiency is practically insensitive to variations of R_{sh} [11]. At the MPP U_{1n} >> AV_t and considering the order of R_{sh} for standard PV module $I_{d\,n} \sim e^{U_{1n}/AV_t} >> I_{shn} = U_{1n}/R_{sh}$. Then, as $I_{ph} > I_{d\,n}$, and therefore, $I_{ph} >> I_{sh\,n}$:

$$\frac{2V_t Az}{R_{sh}\left(I_{ph}+I_0\right)} = \frac{2U_{1n}}{R_{sh}\left(I_{ph}+I_0\right)} = \frac{2I_{shn}}{\left(I_{ph}+I_0\right)} << 1, \tag{5}$$

that makes possible to consider the expression in the square brackets of Eq. (4) is close to one.

Therefore, to simplify the further model the value of R_{sh} will be considered infinitely large ($R_{sh} \rightarrow \infty$). Such consideration is additionally justified for mostly series connection of PV cells in the PV module [8] mainly realized by manufacturers. Also, due to $U_{1n} >> AV_t$, the diode current $I_{d\,n} >> I_0$ and at MPP the reverse saturation current of p-n junction I_0 can be neglected compared to the photocurrent I_{ph}. Then, Eq. (4) can be written as

$$z = W_0\left(e\frac{I_{ph}}{I_0}\right) - 1,$$

and, hence,

$$U_{1n} = V_t A\left(W_0\left(e\frac{I_{ph}}{I_0}\right) - 1\right). \tag{6}$$

Substitution of Eq. (6) in Eqs. (1) and (2) gives the explicit analytical expressions for the load voltage and load current at MPP:

$$I_n = I_{ph} - I_0 e^{W_0\left(e\frac{I_{ph}}{I_0}\right)-1}, \tag{7}$$

$$U_n = U_{1n} - I_n R_s. \tag{8}$$

Maximum power of PV cell at these parameters:

$$P_n = I_n U_n. \tag{9}$$

Then the PV module parameters can be expressed as:

$$I_{nm} = I_n N_p;\ U_{nm} = U_n N_s;\ P_{nm} = I_n U_n N_p N_s. \tag{10}$$

The correctness of the used above approach to MPP parameters determination based on the condition of the maximum power transfer to the series-connected R_s and R_l will be estimated in this part of paper.

In [8] the dependence of fill factor FF of PV module with parasitic resistances on the fill factor FF_0 of ideal PV module without resistive effects is given. The dependence can be used for one PV cell:

$$FF = FF_0\left(1 - \frac{R_s}{U_{OC}/I_{SC}}\right), \tag{11}$$

where U_{OC} and $I_{PV\,cell}$ are the open circuit voltage and the short circuit current of PV cell respectively.

Considering that the product $U_{1n} \cdot I_n$ is the maximum power for the ideal PV cell, expression (11) can be rewritten as:

$$\frac{I_n U_n}{I_{SC} U_{OC}} = \frac{I_n U_{1n}}{I_{SC} U_{OC}}\left(1 - \frac{R_s}{U_{OC}/I_{SC}}\right),$$

or taking into account Eq. (7)

$$U_{1n}-I_nR_s=U_{1n}\left(1-\frac{R_s}{U_{OC}/I_{SC}}\right),$$

from which

$$\frac{U_{1n}}{I_n}=\frac{U_{OC}}{I_{SC}}\,. \tag{12}$$

Verify if obtained expressions for U_{1n} and I_n based on the condition of the maximum power transfer to the series-connected R_s and R_l are identical to Eq. (12). In [12] the approximation of the Lambert W function for large values of the argument is presented:

$$W_0(x)=L_1-L_2+\frac{L_2}{L_1}+\frac{L_2(L_2-2)}{2L_1^2}+\frac{L_2\left(2L_2^2-9L_2+6\right)}{6L_1^3}+$$
$$+\frac{L_2\left(3L_2^3-22L_2^2+36L_2-12\right)}{12L_1^4}+O\left(\left\{\frac{L_2}{L_1}\right\}^5\right),$$

where $L_1=\ln x$ and $L_2=\ln\ln x$.

Due to the high value of ratio I_{ph}/I_0 and, consequently, a large value of argument $x=eI_{ph}/I_0$, the approximation can be confined within the first two terms of the series. Then, from Eqs. (6) and (7):

$$\frac{U_{1n}}{V_tA}=W_0\left(e\frac{I_{ph}}{I_0}\right)-1\approx\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)-\mathbf{ln}\,\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)-1=\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)-\mathbf{ln}\,\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)=$$
$$=\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)\left(1-\frac{\mathbf{ln}\left(1+\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)\right)}{\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)}\right). \tag{13}$$

$$I_n=I_{ph}-I_0e^{W_0\left(e\frac{I_{ph}}{I_0}\right)-1}\approx I_{ph}-I_0e^{\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)-\mathbf{ln}\,\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)-1}=I_{ph}-I_0\frac{I_{ph}/I_0}{\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)}=I_{ph}\left(1-\frac{1}{\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)}\right). \tag{14}$$

Open circuit voltage at $R_{sh}\to\infty$ [13]:

$$U_{OC}\approx V_tA\,\mathbf{ln}\frac{I_{ph}}{I_0}\,. \tag{15}$$

Substitution of Eqs. (13-15) in the Eq. (12) taking into account $I_{ph}\approx I_{PV\,cell}$ gives:

$$\left(1-\frac{\mathbf{ln}\left(1+\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)\right)}{\mathbf{ln}\left(\frac{I_{ph}}{I_0}\right)}\right)=\left(1-\frac{1}{\mathbf{ln}\left(e\frac{I_{ph}}{I_0}\right)}\right).$$

At significant levels of photocurrent $I_{ph}/I_0\to\infty$ obtained equation turns into identity. This means that the proposed approach to determination of MPP parameters based on the maximum power transfer to the series-connected R_s and R_l correctly describes the influence of R_s on the fill factor and, thus, on the maximum power of PV cell, if the condition $I_{ph}/I_0 \to \infty$ takes place, i.e., at a sufficiently high level of solar irradiation.

The basic parameters provided by manufacturers in PV module datasheets are the current (I_{nm}) and the voltage (U_{nm}) at MPP, the open-circuit voltage U_{OCm}, and the short-circuit current $I_{PV\ cellm}$, generally, under standard test conditions (STC), as well as the relative temperature coefficients of the short-circuit current ($\beta_{I_{SC}}$), open-circuit voltage ($\beta_{U_{OC}}$) and maximum power (β_{P_m}).

To take into account the MPP dependence on the solar irradiation level and temperature the value of I_{ph}/I_0 in Eqs. (6) and (7) can be expressed as a function of short-circuit current and open-circuit voltage. Dependence of R_s on PV module operating conditions has insignificant effect on I-V characteristic [4], so R_s is accepted as independent on temperature and solar irradiation level, i.e. $R_s = R_{s,\,ref}$, where "*ref*" means reference conditions (STC). Ideality factor is also considered as a constant value [4, 8, 14], $A = A_{ref}$.

From Eq. (1) at the open-circuit mode, taking into account $R_{sh} \to \infty, I_{ph} \gg I_0$ it can be obtained:

$$\frac{U_{OC}}{R_{sh}} = I_{ph} - I_0 e^{\frac{U_{OC}}{V_t A}} = 0,$$

$$I_0 = I_{ph} e^{-\frac{U_{OC}}{V_t A}}.$$

Then:

$$\frac{I_{ph}}{I_0} = e^{\frac{U_{OC}}{V_t A}},$$

and taking into account temperature coefficients:

$$\frac{I_{ph}}{I_0} = e^{\frac{q_e U_{OCm,ref}\left(1+\beta_{U_{OC}}\left(T-T_{ref}\right)\right)}{N_S A_{ref} kT}}, \tag{16}$$

$$I_0 = I_{ph} e^{-\frac{q_e U_{OCm,ref}\left(1+\beta_{U_{OC}}\left(T-T_{ref}\right)\right)}{N_S A_{ref} kT}}, \tag{17}$$

where T and T_{ref} are the PV module operation temperature and temperature at reference conditions respectively.

The photocurrent dependence on temperature and solar irradiation level can be considered according to the following expression [15]:

$$I_{ph} = I_{ph,ref} \frac{G}{G_{ref}} \left(1 + \beta_{I_{SC}}\left(T - T_{ref}\right)\right), \tag{18}$$

where G_{ref} and G are the solar radiation intensities at the reference and PV module operation conditions respectively;

$I_{ph,\,ref}$ is the photocurrent at the reference conditions.

Then substitution Eq. (10) into Eq. (5) results in:

$$U_{1n} = \frac{kT}{q_e} A_{ref} \left(W_0 \left(e^{\frac{q_e U_{OCm,ref}\left(1+\beta_{U_{OC}}\left(T-T_{ref}\right)\right)}{N_S A_{ref} kT} + 1} \right) - 1 \right). \tag{19}$$

After substitution of Eq. (19) into Eq. (7) and taking into account Eqs. (17) and (18) the explicit analytical expression for the load current at MPP can be found:

$$I_n = I_{ph,ref}\frac{G}{G_{ref}}\left(1+\beta_{I_{SC}}\left(T-T_{ref}\right)\right)\left(1-e^{W_0\left(e^{\frac{q_e U_{OCm,ref}\left(1+\beta_{U_{OC}}\left(T-T_{ref}\right)\right)}{N_S A_{ref} kT}+1}\right)-1-\frac{q_e U_{OCm,ref}\left(1+\beta_{U_{OC}}\left(T-T_{ref}\right)\right)}{N_S A_{ref} kT}}\right). \tag{20}$$

Then using Eqs. (20), (8) and (9) the analytical expressions for the PV cell voltage and power at MPP can be obtained.

To realize the calculations according to the Eqs. (19), (20) and (8) - (10) it is necessary to determine such parameters as $I_{ph,ref}$, $R_{s,ref}$ and A_{ref} at reference conditions. Based on the accepted assumption $R_{sh} \to \infty$ the PV cell model is reduced to a four-parameter model for which [10]:

$$I_{ph,ref} = I_{SCm,ref} / N_p;$$

$$R_{s,ref} = \frac{N_p U_{nm,ref}}{N_s I_{nm,ref}} - \frac{N_p A_{ref} kT_{ref}}{q_e\left(I_{SCm,ref} - I_{nm,ref}\right)};$$

$$A_{ref} = \frac{q\left(2U_{nm,ref} - U_{OC,ref}\right)}{N_s kT_{ref}\left(\frac{I_{nm,ref}}{I_{SCm,ref} - I_{nm,ref}} + \ln\left(1 - \frac{I_{nm,ref}}{I_{SCm,ref}}\right)\right)}.$$

PV module temperature can be estimated from the expression [1]:

$$T = T_A + \frac{T_{NOCT} - 20°C}{800}G,$$

where T_A is the ambient temperature;

T_{NOCT} is the PV module temperature at normal operating cell temperature (NOCT) conditions also given in manufacturer's datasheet.

To test the accuracy of the proposed approach the calculations of the maximum power P_{nm} at different temperatures and solar irradiation levels for several types of silicon PV modules were carried out. The results of calculations marked as "LambF" are shown in Table 1. Operation conditions of PV modules, the experimentally determined power values from a building integrated photovoltaic facility at the National Institute of Standards and Technology (NIST), as well as the calculation results obtained in accordance with the King's (King) and the five-parameter (5-param) models of PV module, presented in the same table, as well as required input data were taken from [4].

In Table 2 the relative deviations of calculated results from experimentally determined maximum power values are shown for corresponding models.

As can be seen from Table 2, the results obtained by means of the proposed approach quite correctly describe the behavior of monocrystalline and polycrystalline silicon PV modules.

As regards the thin film PV modules, in the case of proposed approach the deviation is 5.01% at a solar irradiation intensity of 696 W/m^2 and rises to 26.4% when intensity decreases to 189.8 W/m^2. Thus, at the intensity of 189.8 W/m^2 the accuracy of proposed approach is three times worse than for the King's model and two times worse than the accuracy of 5-parametric model. This result can be connected with incorrect value of R_s in the case of the thin-film PV modules. It was found the R_s value obtained from the Eq. (15) is negative that can be explained by incorrect assumption $R_{sh} \to \infty$ for thin-film PV modules. The relatively low value of R_{sh} for thin-film PV cell results in the failure of inequality (5) especially at low solar irradiation level when, according to our estimation, the left side of inequality (5) reaches 0.6. Besides, at low irradiation levels (and, hence, at low I_{ph} values) the Eq. (12) is not held exactly for proposed approach that results in discrepancy between the experimental MPP parameters and calculated ones.

Also the proposed approach was tested by calculation of I_{nm}, U_{nm} and P_{nm} values for NOCT conditions basing on STC data for PV modules, which datasheets contain parameters at STC and NOCT conditions. In addition, the maximum power temperature coefficient β_{P_n} was calculated. Comparisons of the calculated MPP parameters with their datasheets values, as well as corresponding relative deviations of parameters are shown in Table 3.

Table 1

Results of the maximum power calculation in comparison with experimental data at variable operating conditions, W

Type of PV module	G, W/m^2	1000.0	882.6	696.0	465.7	189.8
	T, °C / Source	25.0	39.5	47.0	32.2	36.5
Monocrystalline silicon PV module	NIST, [4]	133.4	109.5	80.1	62.7	23.8
	King, [4]	133.4	111.4	82.0	61.1	22.5
	5-param, [4]	133.4	110.6	82.4	61.0	22.3
	LambF	133.4	109.8	83.9	61.2	24.7
Polycrystalline silicon PV module	NIST, [4]	125.8	106.8	77.4	56.6	21.2
	King, [4]	125.8	109.3	79.1	56.9	18.5
	5-param, [4]	125.8	105.6	78.1	55.8	20.6
	LambF	125.8	103.1	78.2	56.6	22.6
Thin-film silicon PV module	NIST, [4]	104.0	83.7	59.9	40.8	14.4
	King, [4]	104.0	87.3	62.3	43.2	15.7
	5-param, [4]	104.0	85.5	62.3	44.3	16.3
	LambF	104.0	84.1	62.9	46.0	18.2

Table 2

Relative deviations of the calculated results from the experimental values of maximum power, %

Type of PV module	G, W/m^2	1000.0	882.6	696.0	465.7	189.8
	T, °C / Source	25.0	39.5	47.0	32.2	36.5
Monocrystalline silicon PV module	King	0	1.74	2.37	2.55	5.46
	5-param	0	1.00	2.87	2.71	6.30
	LambF	0	0.27	4.74	2.39	3.78
Polycrystalline silicon PV module	King	0	2.34	2.20	0.53	12.74
	5-param	0	1.12	0.90	1.41	2.83
	LambF	0	3.46	1.03	0.00	6.60
Thin-film silicon PV module	King	0	4.30	4.01	5.88	9.03
	5-param	0	2.15	4.01	8.58	13.19
	LambF	0	0.42	5.01	12.75	26.39

Table 3

Comparison of the calculated MPP parameters with PV module datasheets values at NOCT conditions

Name of PV module	Datasheet values				Calculated values				Deviation, %			
	I_{nm}, A	U_{nm}, V	P_{nm}, W	β_{P_n}, %/K	I_{nm}, A	U_{nm}, V	P_{nm}, W	β_{P_n}, %/K	I_{nm}	U_{nm}	P_{nm}	β_{P_n}
1	2	3	4	5	6	7	8	9	10	11	12	13
Monocrystalline silicon PV modules												
LG300N1K-G4	7.38	29.50	218.00	-0.38	7.46	30.37	226.68	-0.383	1.14	2.94	3.98	0.66
SW 270 mono	7.12	28.30	201.30	-0.45	7.12	28.54	203.24	-0.432	0.01	0.86	0.96	3.92
YL300C-30b	7.30	30.30	220.80	-0.38	7.39	30.31	224.03	-0.376	1.23	0.05	1.46	1.17
Q.PEAK-G3 280	7.03	29.60	208.00	-0.42	7.22	29.39	212.20	-0.409	2.71	0.71	2.02	2.65
Q.PEAK BLK-G3 250	6.60	27.92	184.30	-0.43	6.67	27.97	186.44	-0.419	1.00	0.18	1.16	2.58
JAM6(L) 60-290/PR	7.34	28.89	212.02	-0.41	7.37	29.62	218.30	-0.412	0.42	2.52	2.96	0.55
JC250S-24/Bb	6.57	28.00	184.00	-0.43	6.70	27.88	186.67	-0.445	1.93	0.44	1.45	3,42
LDK-180D-24	3.96	32.80	130.00	-0.47	3.98	33.11	131.74	-0.482	0.49	0.93	1.34	2.51

Continuation of the Table 3

1	2	3	4	5	6	7	8	9	10	11	12	13
Average value									1.11	1.08	1.92	2.18
Polycrystalline silicon PV modules												
STC 260P	6.80	27.70	189.00	-0.43	6.92	27.79	192.44	-0.411	1.83	0.33	1.82	4.51
Q.PRO-G4 265	6.75	29.01	195.70	-0.41	6.93	28.50	197.59	-0.423	2.71	1.75	0.97	3.05
TSM-250 PC/PA05	6.70	27.00	181.00	-0.43	6.67	27.95	186.29	-0.446	0.52	3.52	2.92	3.61
SW 235 poly	6.28	27.10	170.40	-0.48	6.31	27.45	173.27	-0.482	0.51	1.29	1.68	0.35
WSP-260P6	6.74	28.21	190.14	-0.43	6.75	29.04	196.14	-0.416	0.19	2.96	3.15	3.36
YL245P-29b	6.54	27.20	177.90	-0.45	6.57	27.71	182.17	-0.449	0.52	1.87	2.40	0.26
INE-255-6PB	6.74	28.10	190.00	-0.41	6.77	28.34	191.98	-0.401	0.50	0.86	1.04	2.31
JT300PMe	6.30	34.30	215.90	-0.43	6.37	34.84	221.91	-0.437	1.11	1.57	2.78	1.53
EX260P-60	7.03	28.00	196.90	-0.44	6.91	28.24	195.19	-0.443	1.68	0.85	0.87	0.16
Average value									1.06	1.67	1.96	2.13
Thin-film silicon PV modules												
GS STFS	3.60	30.80	111.00	-0.21	3.49	29.37	102.65	-0.552	2.93	4.63	7.52	162.90
U-EA 100	1.53	48.80	74.40	-0.35	1.44	48.53	69.88	-0.591	5.88	0.56	6.07	68.93
TW-TF 130	0.80	122.80	99.00	-0.29	0.75	122.71	91.47	-0.483	6.24	0.07	7.61	66.39
Average value									5.02	1.75	7.07	99.41

As can be seen from Table 3, the proposed approach provides correct description of the MPP behavior for several monocrystalline and polycrystalline PV modules at variable temperature and irradiation conditions. However, in the case of thin-film PV modules the significant discrepancies between the calculated and experimental values take place as before.

Conclusions

1. Analytical expressions for PV module current, voltage and power at MPP based on the Lambert W function have been obtained. Photocurrent, reverse saturation current of p-n-junction, ideality factor and series resistance are used as variables in these expressions.
2. Based on the obtained analytical expressions and PV module data from manufacturer's datasheet the non-iterative approach has been proposed to predict the PV module electrical parameters at MPP at different temperatures and levels of solar irradiation. Calculation of MPP electrical parameters for several PV modules realized by proposed approach shows generally good accuracy in maximum power determination, which is comparable with more complicated models, except the case of thin-film PV modules.

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