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KVALITETA **ODREĐIVANJ**A OSNOVNIH PARAMETARA **ELEKTRIČNOG MODELA** FOTONAPONSKOG MODULA IZ NAZIVNIH PODATAKA

QUALITY OF BASIC PARAMETERS CALCULATION FOR PHOTOVOLTAIC MODULE ELECTRICAL MODEL USING MODULE NOMINAL DATA

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Izvorni znanstveni članak

Sažetak: *U ovom istraživanju se rezultati najčešće korištenog matematičkog modela za opis stanja električnih veličina u fotonaponskim modulima uspoređuju sa rezultatima mjerenja. Korištenje ovog modela primjenjivo je u većini naprednih sustava za poboljšanje korisnosti fotonaponskih sustava. Da bi mogli koristiti model fotonaponskog modula potrebno je poznavati njegove parametre. Ovdje je prikazano određivanje osnovnih parametara serijskog i paralelnog otpora, ekvivalentne diode i strujnog izvora isključivo pomoću nazivnih podataka fotonaponskog modula. Rezultati ovog proračuna uspoređeni su sa konkretnom radnom točkom maksimalne radne snage.*

Ključne riječi: *električni model, fotonaponski modul, nazivni podaci, parametri*

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Abstract: *In this research the results of most commonly used mathematical model for description of electrical values in PV modules are compared to measured results. This model is usable in most of advanced systems for PV system energy production utility improvement. In order for these models to be used it is necessary to provide the correct values of model parameters. In this paper the method for determining basic parameters of serial and parallel resistances, equivalent diode and current source entirely using PV module nominal data. The results of this method are compared for with specific operating point of maximum power.*

Key words: *electrical model, photovoltaic module, nominal data, parameters*

1. INTRODUCTION

The usage of electrical modelling of PV modules is present in most of the advanced computer oriented applications for PV technology, such as Maximum Power Point (MPP) tracking systems in [1]. These applications are introduced in order to increase the efficiency of PV module energy production. The accuracy of PV module electrical model can significantly influence the efficiency of the whole system, like in [2].

The most common PV module electrical model is Single Diode Model (SDM). In this research SDM parameters are gained using only nominal data of PV module, and then compared with parameters provided from measured U-I characteristics. The measuring system from which these data are gained is not described in this paper, and data are used “as is”.

2. PHOTOVOLTAIC MODULES

The PV module is usually described with nominal data for three specific operating points. They are open-circuit, short-circuit and MPP operating points. Since the open-circuit is defined with no current in load circuit, this operating point can be described by open-circuit voltage while current is assumed as 0 A. In similar way short-circuit operating point is defined with maximum current in load circuit and load voltage is assumed zero. Both of these operating points are not providing any power into the load due to no voltage or no current. The MPP operating point is the most efficient operating point of PV module. Therefore, the current and voltage are not equal to zero, and are providing certain power.

Figure 1 PV module DSP-10M, 10W

Any other PV module operating point will provide decrease of power compared to MPP operating point, regardless of load current or load voltage increase or decrease. These operating points are described in detail in [3]. The PV module provided in Figure 1. is used for comparison of modelled and measured U-I characteristics.

The nominal data is describing the ideal operation conditions of PV module. These data are provided in laboratory operation and very often does not represent the true state of PV module in real application. For example the temperature of cells in PV module is considered to be the same as the ambient temperature. This is true only for the start of energy production since the current will increase the cell temperature, and therefore change the working conditions. The same influence can be introduced for cooling by the wind. The wind speed is also to be considered if trying to estimate the PV cell temperature from the ambient temperature. Nominal data for PV module used in this research is presented in Table 1.

Table 1 Nominal data of PV module DSP-10M

PV module parameter	Nominal value
Model	DSP-10M
P_M	10 (±3%) W
U_M	9.00 V
I_M	1.11 A
U_{PH}	10.80 V
I_{KS}	1.28 A
T_{noct}	-45 ÷ 80 °C
U_{max}	60 DC V
Dimensions	284 x 350 x 17 mm
Standard test conditions: AM = 1.5; H = 1000 W/m^2; T = 25 °C	

The nominal open-circuit voltage can provide the number of cells used in PV module. Single cell voltage is provided with average of 0.7 V. Therefore, the voltage of 10.80 V will be reached with 15 cells in serial connection.

3. SINGLE DIODE MODEL OF PHOTOVOLTAIC MODULE

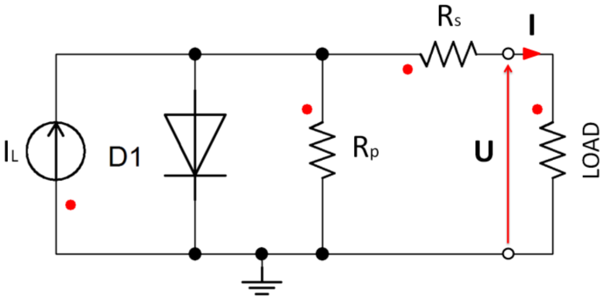

Figure 2 SDM of PV module

The Single Diode Model (SDM), presented in Figure 2., is the most common model for describing the PV module. It represents all significant impacts on electrical energy production from PV module, such as available ambient light, PN junction in cells and internal current/voltage losses, similar to [4]. The voltage and current dependence of PV module output is presented trough equation (1).

$$I = I_L - I_0 exp\left(\frac{U+R_S I}{mU_T}\right) - \frac{U+R_S I}{R_P} \tag{1}$$

The light impact is presented trough current source I_L which is linear to available irradiation on surface of the PV module. This is also the highest possible output current of the PV module. The PN junction inside cells is represented as a diode in parallel connection with the load. This diode will provide upper limit on output voltage while reducing the output current by omitting differential current. The number of diodes in serial connection inside the model is determined by the number of PV cells in the PV module. The diode is determined by dark current I_0 and parameter m (1.3 standard for monocrystalline). The serial resistance represents voltage losses and parallel resistance represents current losses inside the PV module compared to ideal state. These losses are present due to heat, junctions, etc.

In order to model the PV module it is necessary to provide parameters of the SDM, like in [5]. Therefore, first the function of PV module U-I characteristic must be provided. It is selected that $f(U,I)$ is in fact the PV module output current, and is determined using itself inside the calculation. It is possible to combine the equation (1) for the open-voltage, short-circuit and MPP operating points into equation (2), like presented in [6].

$$f(I,U) = I_L - \frac{U+R_S I - R_S I_L}{R_P} - I_L exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right) + \frac{U_{PH}-R_S I_L}{R_P} exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right) \tag{2}$$

Since the function $f(U, I)$ is in fact the output current I, it is possible to define equation (3). In order to gain the differential of current over voltage it is possible to rearrange equation (3) into (4).

$$dI = dI\frac{\partial f(I,U)}{\partial I} + dU\frac{\partial f(I,U)}{\partial U} \tag{3}$$

$$\frac{dI}{dU} = \frac{\frac{\partial f(I,U)}{\partial U}}{1-\frac{\partial f(I,U)}{\partial I}} \tag{4}$$

In order to solve the equation (4) it is necessary to provide differentials of function $f(U, I)$ over current I and voltage U respectively. The differential of $f(U, I)$ over voltage U is provided in steps trough (5), (6) and (7). The function provided in equation (8) will be inserted into equation (4).

$$\frac{\partial f(I,U)}{\partial U} = \frac{\partial}{\partial U}\left[I_L - \frac{U+R_S I - R_S I_L}{R_P} - I_L exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right) + \frac{U_{PH}-R_S I_L}{R_P} exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right)\right] \tag{5}$$

$$\frac{\partial f(I,U)}{\partial U} = -\frac{1}{R_P} - I_L\frac{1}{m\cdot U_T} exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right) + \frac{U_{PH}-R_S I_L}{R_P}\frac{1}{mU_T} exp\left(\frac{U+R_S I - U_{PH}}{mU_T}\right) \tag{6}$$

$$\frac{\partial f(I,U)}{\partial U} = \frac{-I_L R_P + U_{PH} - R_S I_L}{m R_P U_T} \cdot exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) - \frac{1}{R_P} \qquad (7)$$

$$\frac{\partial f(I,U)}{\partial U} = -\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) - \frac{1}{R_P} \qquad (8)$$

The differential of *f(U, I)* over current *I* is provided in steps trough (9), (10) and (11). The function provided in equation (12) will be inserted into equation (4).

$$\frac{\partial f(I,U)}{\partial I} = \frac{\partial}{\partial I}\left[I_L - \frac{U + R_S I - R_S I_L}{R_P} - I_L exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) + \frac{U_{PH} - R_S I_L}{R_P} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right)\right] \qquad (9)$$

$$\frac{\partial f(I,U)}{\partial I} = -\frac{R_S}{R_P} - I_L \frac{R_S}{m \cdot U_T} exp\left(\frac{U + R_S I - U_{PH}}{m \cdot U_T}\right) + \frac{U_{PH} - R_S I_L}{R_P} \frac{R_S}{m U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) \qquad (10)$$

$$\frac{\partial f(I,U)}{\partial I} = \frac{-R_P I_L R_S + R_S(U_{PH} - R_S I_L)}{m R_P U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) - \frac{R_S}{R_P} \qquad (11)$$

$$\frac{\partial f(I,U)}{\partial I} = -\frac{R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) - \frac{R_S}{R_P} \qquad (12)$$

If (8) and (12) is inserted in (4) it is possible to provide final solution for differential of current *I* over voltage *U* as in equation (13).

$$\frac{\frac{\partial f(I,U)}{\partial U}}{1 - \frac{\partial f(I,U)}{\partial I}} = \frac{-\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) - \frac{1}{R_P}}{1 + \frac{R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} exp\left(\frac{U + R_S I - U_{PH}}{m U_T}\right) + \frac{R_S}{R_P}} \qquad (13)$$

From empirical data it can be concluded that changes of output current *I* due to change of output voltage *U* is dependant only to parallel resistance R_P in case of short-circuit operating point, and is described in (14). Finally, equation (15) can be reached when combining (13) and (14). This conclusion is also available in [3].

$$\left.\frac{dI}{dU}\right|_{I=I_L, U=0} = \left.\frac{\frac{\partial f(I,U)}{\partial U}}{1 - \frac{\partial f(I,U)}{\partial I}}\right|_{I=I_L, U=0} = -\frac{1}{R_P} \qquad (14)$$

$$\frac{-\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} exp\left(\frac{R_S I_L - U_{PH}}{m U_T}\right) - \frac{1}{R_P}}{1 + \frac{R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} exp\left(\frac{R_S I_L - U_{PH}}{m U_T}\right) + \frac{R_S}{R_P}} = -\frac{1}{R_P} \qquad (15)$$

From fact that output power *P* is maximum for MPP operating point it can be concluded that changes of output current *I* due to change of output voltage *U* is dependant to ratio of MPP current I_M and MPP voltage U_M, and is described in (16). Finally, equation (17) can be reached when combining (13) and (16). This conclusion is also available in [3].

$$\left.\frac{dI}{dU}\right|_{I=I_M, U=U_M} = \left.\frac{\frac{\partial f(I,U)}{\partial U}}{1 - \frac{\partial f(I,U)}{\partial I}}\right|_{I=I_M, U=U_M} = -\frac{I_M}{U_M} \qquad (16)$$

$$\frac{-\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} \cdot exp\left(\frac{U_M + R_S I_M - U_{PH}}{m \cdot U_T}\right) - \frac{1}{R_P}}{1 + \frac{R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} exp\left(\frac{U_M + R_S I_M - U_{PH}}{m U_T}\right) + \frac{R_S}{R_P}} = -\frac{I_M}{U_M} \qquad (17)$$

In the same way as for the case of short-circuit operating point it can be concluded that changes of output current *I* due to change of output voltage *U* is dependant only to serial resistance R_S for the open-voltage operating point, and is described in (18). Finally, equations (19) and (20) can be reached when combining (13) and (18).

$$\left.\frac{dI}{dU}\right|_{I=0, U=U_{PH}} = \left.\frac{\frac{\partial f(I,U)}{\partial U}}{1 - \frac{\partial f(I,U)}{\partial I}}\right|_{I=0, U=U_{PH}} = -\frac{1}{R_S} \qquad (18)$$

$$\frac{-\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} \cdot exp\left(\frac{0}{m U_T}\right) - \frac{1}{R_P}}{1 - \frac{-R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} exp\left(\frac{0}{m U_T}\right) + \frac{R_S}{R_P}} = -\frac{1}{R_S} \qquad (19)$$

$$\frac{-\frac{I_L R_P - U_{PH} + R_S I_L}{m R_P U_T} - \frac{1}{R_P}}{1 + \frac{R_S[R_P I_L - U_{PH} + R_S I_L]}{m R_P U_T} + \frac{R_S}{R_P}} = -\frac{1}{R_S} \qquad (20)$$

Since the short-circuit output current can be assumed the same as the current source I_L it is necessary only to determine the serial and parallel resistances from equations (15), (17) and (20).

4. MODELED AND MEASURED RESULTS

The modelled result parameters for SDM of PV module presented in Table 2. are adjusted to nominal data in such way that it is suitable for the MPP operating point using described method. The modelled values are gained using *Solve* command in Matlab software. The diode is provided as standard element inside simulation package, serial connection of 15 such diodes, as described before. The measured values for model are provided using measured operating points in Simplorer SC 7.0.

Table 2 Calculated SDM parameters

PV module parameter	Modeled value	Measured value
R_p / Ω	71.8	129.0
R_s / Ω	8.1	0.1
I_L / A	1.28	1.28

For purpose of this research the measured parameters from Table 2. are all inserted into the equations (15), (17) and (20) in order to determine the accuracy of these equations.

Table 3 Confirmation of equations (15), (17) and (20)

Equation	Left side	Right side	Δ / %
15	-0,0077	-0,0078	-0,075
17	-0,1460	-0,1233	15,497
20	-1,5411	-10,000	-548,908

From the results in Table 3. It can be seen that equation (15) has very small difference between left and right side. Therefore, this equation can be used for determination of R_P in SDM of PV module. Equation (17) can be described as good for rough approximation of R_P and R_S from available current and voltage in MPP. In this case equation (20) did not give good approximation of R_S from nominal data.

In order to determine real parameters for electrical model of PV module it is not sufficient to provide them from nominal data of PV module. The parallel resistance R_P has usually rather high value (100-300 Ω) and will be somewhat good determined by this method. The serial resistance R_S has usually rather low value (0.1-1 Ω) and therefore can introduce significant approximation error. The parameters for SDM of PV module must be determined using the whole measured U-I characteristic for specified PV module.

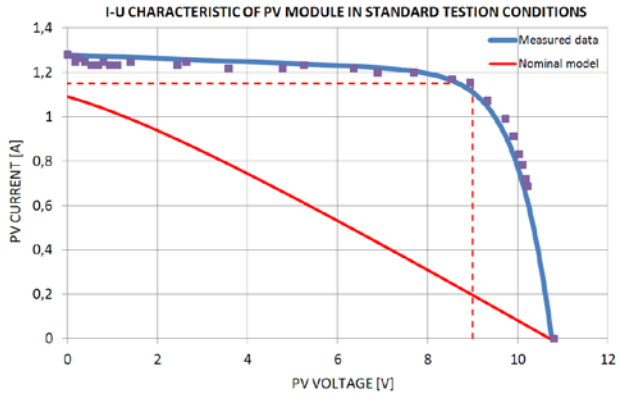

Figure 3 Modelled and measured PV module U-I characteristics

In presented results it can be seen that parallel resistance is somewhat accurate, while serial resistance is rather poorly describing the PV module measured U-I characteristic. In Figure 4. the U-P characteristic shows error for modelled result of MPP tracking. The operating point of MPP is very poorly described using SDM with calculated parameters.

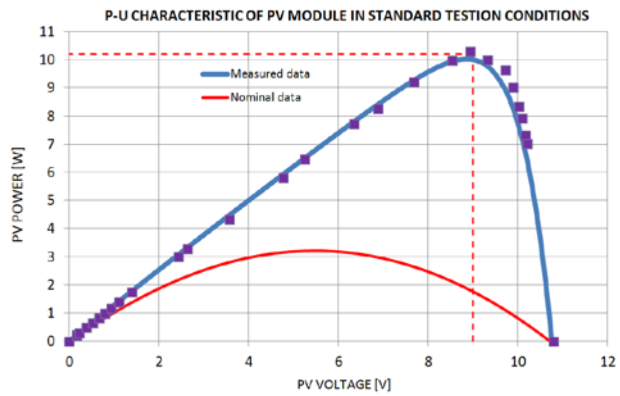

Figure 4. Modelled and measured PV module U-P characteristics

5. CONCLUSION

The electrical model of PV module can be defined using nominal data. Parameters of SDM will be gained using simple calculations, but with very different tolerances. If current source is defined with short-circuit current, basic parameters of R_P and R_S are also available as basic parameters of SDM. The parallel resistance R_P has rather high value, and therefore can be roughly gained using described method. The serial resistance R_S has rather low value, and therefore can be gained using described method, but with very low accuracy. The result model will give poor results compared with measured U-I characteristic of specified PV module, but with the possibility of improvement if more accurate nominal data is provided. In order to get more accurate SDM model it is necessary to gain the parameters using the whole measured U-I characteristic of PV module.

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