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THE MODEL OF PHOTOVOLTAIC CELL WITH CONSIDERATION OF LOAD VARIABILITY

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Abstract: *The paper proposes designing of a model of photovoltaic cell operation in real conditions. The method of residua estimation is applied, modified according to verification of the obtained models. The choice of the optimal model is a final effect of the article.*

Keywords: *modeling, residua estimation, photocell*

INTRODUCTION

The acquaintance of the dynamic state and the structure of the photovoltaic system allows to describe operation in any conditions. It enables possible building of prognostic models of the system behavior as a function of the time during the dynamic evolution. It means the use of models forecasting the values of symptoms of the technical state.
The equalizations describing maintenance of the system in function of time during the dynamic evolution is usually not well-known. This is why a need arises to adapt new investigation tools of the dynamic state. In consequence, grows the meaning of the experimental verification of the models.

1 THE MEASURING STAND

The laboratory measurement stand is presented on Figure 1.

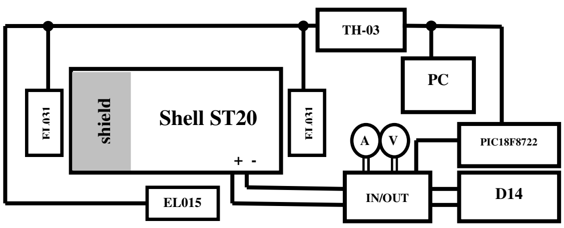

Fig.1: Block diagram of the measuring stand [4]

The laboratory measuring stand includes (Fig.1): a photovoltaic module Shell ST20 [4] of outer size 748×328×35mm (the weight of 4100g), a decade resistor D14 kl. 0.1, a TH-03 converter (3-channels, the dimensions 125×60×30, computer communication through a series port COM; *T* temperature measurement: an EL015 sensor of resolution of $\pm 0.01^{\circ}C$; *D* lighting quality measurement: two EL031 sensors of resolution of $\pm 0.1\%$), the conductors with plugs, a PC computer with a software developed by manufacturer of the Pico measurement converters (temperature and lighting quality measurement), microcontroller PIC18F8722 (an AC-converter: voltage measurement with the help of a voltage divider, current measurement with a shunt), digital meters (verification of accuracy of the AC-converter read-out); an intermediate I/O system (including a voltage divider provided with a Zener diode, protecting the AC converter against overvoltage and a shunt for current measurement) designed for physical connecting the photovoltaic module, resistor, meters, and microcontroller.
Reception, processing, and transmission (RS232) of the measured values at the microcontroller level have been implemented with the help of C Language. The final application (developed in the Delphi environment [3]) fulfils many functions, among others ensures two-directional communication with the microcontroller (e.g. possible changes in signal sampling frequency). The application computes average value of the illumination quality *D*, plots the I=f(U) characteristics, and allows for exporting the measurement results to the Excell Sheet or recording them in the form of a graphic plot. It is provided with an approximation function, etc [2,3].
The laboratory stand is used for measuring and database archiving [2,3,5] of the following parameters, with the use of previously designed applications: *D* – the lighting quality expressed in the percent relative scale, *T* - the

environment temperature in Celsius scale, I – the output current [A], U – the voltage drop at the load [V].

2 PROPOSAL OF THE MODEL

The paper proposes the use of a new supplementary model containing outwardly following parameters:
- the voltage on connectors of the loaded photovoltaic module – U,
- the current generated by the module – I,
- the temperature of the nearest environment (airs) round the module – T,
- the percentile quality of the lighting of the surface round the module – D (at the assumption of the steady lighting of the all surface of the module, what in solar power stations is accorded [1]),
- the percentile estimated active (efficient) surface of the module – S (in the standard-model S =100%).

The model, at the assumption of the constant load, assumes symbolic form:

$$\mathrm{I} = \mathrm{f}(\mathrm{U}, \mathrm{T}, \mathrm{D}, \mathrm{S}) \tag{1}$$

Parameters of the model (1) one can mark with the method of residua estimation.

Several mathematical models have been developed that describe operation of the photovoltaic panels. First of all, a model describing dependence of the voltage of the charged photovoltaic panel on the lighting level D and temperature T has been created. For this goal a approximation of a function of many variables was used, based on the "modeling measurements" for which S=100%. The base functions have been assumed on the grounds of empirical and literature data [4] as an exponential function of the Ae^{By} form for lighting quality D and a polynomial function for the environment temperature T. Hence, the output function formula, for which the coefficients are to be defined, is as follows:

$$Q(x, y) = a_0 + \sum_{j=1}^{m_x} a_j T^j + \sum_{j=1}^{m_y} a_{m_x+j} e^{jBD} \tag{2}$$

where: a_j - coefficient of the output function, m_x - degree of the polynomial function, m_y - degree of the exponential function of e-base, B - an empirical constant.

According to the approximation principles [7] such a set of the a_j coefficients is sought as to obtain minimal value of the mean-square point error E (3):

$$E = \sum_{i=0}^{n} \left(f_i - Q(T_i, D_i)\right)^2 \tag{3}$$

The necessary condition for E error minimization includes computation of the derivatives with regard to all the coefficients of the equation E according to the relationship (4), that allows to obtain a system of $(m+1)$ linear equations, where $m=m_x+m_y$, m - being maximal number of the a coefficient of the equation (2).

$$\sum_{j=0}^{m} \frac{\partial E}{\partial a_j} = 0 \tag{4}$$

The calculation provided various forms of the models U=f(T,D) for various parameters that were constant during a single measurement session – the receiver loads.

Afterwards, an attempt was made to find an I=f(U,D,T) model with consideration of varying load during a single measurement session. For purposes of the "modeling measurements" a constant lighting value D for each of the series and S=100% have been assumed. The problem was considered based on the formula (5) known from the theory of equivalent diagrams [1] of the photovoltaic modules, the electric scheme of which is shown in Fig.2:

$$I = I_{ph} - I_D = I_{ph} - I_0 \left[\exp\left(\frac{qU}{k(T + 293.15)} \right) - 1 \right] \tag{5}$$

where: I_0 – a "dark" (saturation) diode current, q – the elementary charge ($1{,}6 \cdot 10^{-19}$As), k – the Boltzmann constant ($8{,}65 \cdot 10^{-5}$ eV/K), T – temperature [^oC].

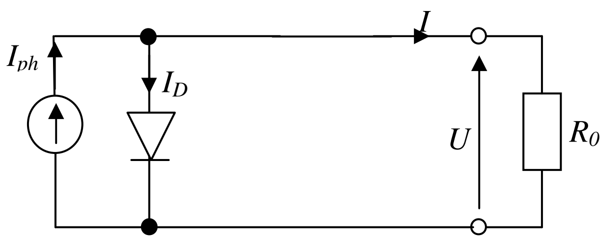

Fig.2: Ideal equivalent photocell diagram for a three-parameters model [1]: R_0 – the charge resistance, I_{ph} – the current flowing in the irradiated cell, I_D – the current of a large-surface diode, I – the load current, U – voltage drop [V] of the receiver R_0

Finally the following formula has been assumed for the approximation:

$$I = I_{ph} + I_0 \left[\exp\left(\frac{BU}{(T + 293.15)} \right) - 1 \right] \tag{6}$$

where: I_{ph}, I_0 – the coefficients obtained in result of the approximation provided the condition (4) is met, B – an empirically estimated constant – in the range from 0 to 500.

According to the expectation, the I_0 coefficient takes negative values.

3 THE METHOD OF RESIDUES

In the method of residua estimation the measurement result denoted by y is compared to the signal ŷ generated by the model while generating the residuum r.

$$r = y - \hat{y} \tag{7}$$

In an ideal case and correct operation of the object the residuum value may be equal to zero, while any damage or failure should give its non-zero value.
Practically the model is inaccurate for the segmental linearisation of the output function and the disturbance of real measuring values. The residues may take non-zero values even in case of non-deviated damage of the module. So, there moves the one space of the uncertainty of the model for residuum round the value 0.
For taking into account of the variability of the load one constructs multidimensional spaces of restrictions. Additionally one proposes to use the method of residua estimation to the verification of obtained patterns with real performance of measurement for the purpose of the execution of the choice of the best pattern. The criterion is based on the minimization of the average value of the residuum r_{av} (8).

$$r_{av} = \frac{1}{n}\sum_{j=1}^{n}\left|y_j - \hat{y}_j\right| \tag{8}$$

where: n – the number of measurement samples taken during faultless and break-down operation.

In case of the ambiguity in the estimation of patterns on the basis the mean value residuum applies additional criterion of estimation of patterns [6].

4 PRELIMINARY RESULTS OF CALCULATIONS

On Fig. 3 are present the U=f(D) patterns for example constant temperature values T=22.6ºC. The green line denotes the model pattern, while the red dots are for the original samples archived during the laboratory measurements.

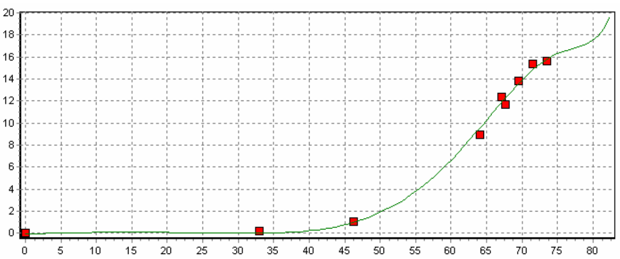

Fig.3: Mapping of the U[V] voltage as a function of the lighting quality D[%] for the environment temperature T=22.6ºC

Example visualization of further 2000 samples (archived during more than ten days under a constant load) for the obtained U=f(T,D) model is shown in Fig.4. The variation ranges of m_x and m_y of the formula (2) from 1 to 10 have been taken into account. The least value obtained from the formula (4) served as a criterion of the model choice, characterized by m_x=5, m_y=6 and the constant B=0.033. The modeling measurements have been carried out for the ranges D from 0% to 82.42%, T from 17.24ºC to 31.11ºC.

Verification of the U=f(T,D) model with the use of the formula (8) was successful: upon shielding of about 38 per cent of the photovoltaic panel working surface the average absolute residue value accounted from 4 consecutive samples before and after the shielding increased from $|r_{av}|$=0.332V to $|r_{av}|$=*0.995V*. The relative values amounted to $|r_{av\%}|$=2.14% for the unshielded panel and $|r_{av\%}|$=6.41% for the shielded panel.

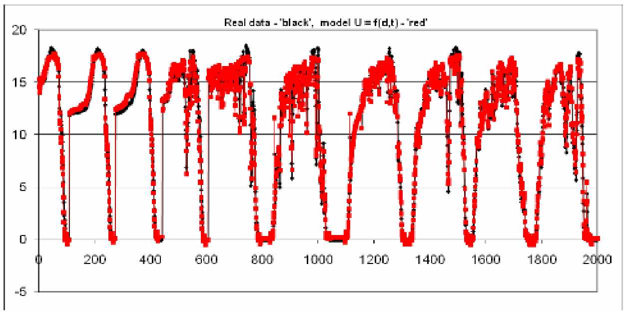

Fig.4: The U voltage time-patterns: black – actual measurement samples, red – the values obtained from the model

The use of the formulas (6, 3, 4) allowed for similar verification of the I=f(U,T,D) model for a constant D value. For D=84.5% the parameters I_{ph}=405.21, I_0=-8.71*10^{-9} and B=410 have been obtained. The current-voltage characteristics obtained in this case give evidence of correctness of the mathematical model. Comparison of the actual (black) and model (red) characteristics is presented in Fig.5.

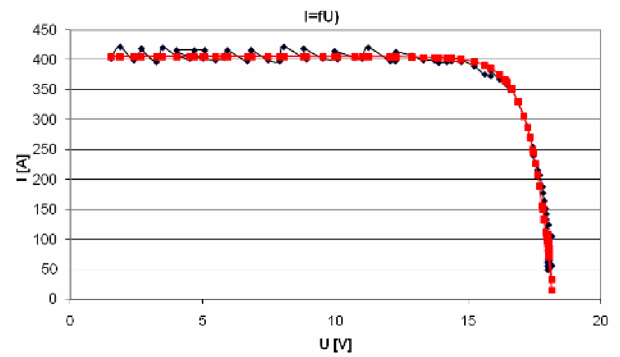

Fig.5: Results of the I=f(U) modeling obtained for D=84.5%

Similar results for the value D=86.46% gave I_{ph}=597.62, I_0=-1.47·10^{-8} and B=410. This case is presented in Fig.6.
Discussion of the results obtained for various values of the lighting D gives evidence that the model parameters I_{ph} and I_0 depend on the D parameter, while B remains unchanged.

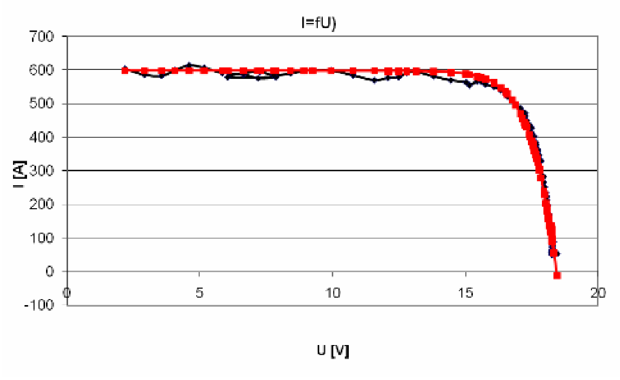

Fig.6: Results of the I=f(U) modeling obtained for D=84.46%

The next stage consists in verification of the current-voltage characteristics usefulness for assessing the condition of the considered panel. This was achieved by comparing the I=f(U) characteristics obtained by shielding 30% (black) and 60% (green) of the photovoltaic panel working surface to the red model curve of Fig.6. The results are shown in Fig.7.

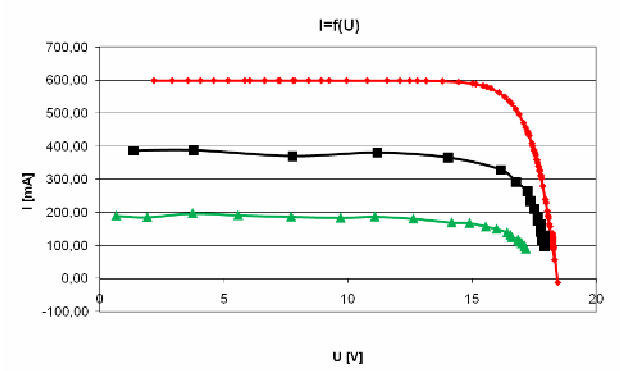

Fig.7: The I=f(U) model characteristics patterns obtained by shielding a part (30% and 60%) of the photovoltaic panel working surface for D=86.46% (the curve colours explained in the text)

Additionally, the effect of available photovoltaic panel working surface on its operation in the area of the maximal power point *P* has been checked. The results are shown in Fig.8 (the colour codes are the same as in Fig.7).

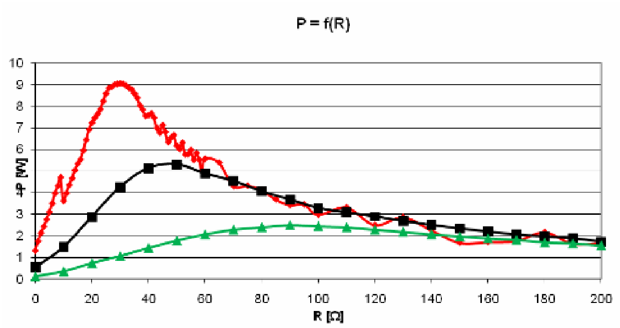

Fig.8: The P=f(R) characteristics patterns obtained by shielding a part (30% and 60%) of the photovoltaic panel working surface for D=86.46% (the curve colours explained in the text)

The above figure shows that the interpretation of the results up to maximal load with the resistance of 100Ω appears in the future particularly important and useful for the considered panel. It might be supposed that similar is the case of other panels. Moreover, it should be noticed that the maximal power point shifts towards greater values with decreasing active surface of the considered panel.

5 CONCLUSIONS

The procedure of the verification of models presented in this paper enables obtaining satisfactory results in the process of photovoltaic cell modeling. The model I=f(U,T,D) may be used for assessment of the tested object state in the future. Further attempts aim at designing a model that would consider varying lighting value *D* and precisely determined ranges of the varying load.

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