Photovoltaic Panel Modeling in MATLAB® Environment

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Abstract. *This article is focused on the original photovoltaic panel model identification method. The method is based on the measured characteristics $i = f(v)$ for given irradiation. The system can automatically create a mathematical model for a particular panel and a specific temperature. Attention is paid to the approximation error progress, which is at minimum in the Maximum Power Points (MPP). During the application of well-known Shockley's equation to the entire panel the nonlinear and parametric power losses are corrected. This approach provides an accurate approximation with good agreement with measured data. The method can be applied to any measured photovoltaic panel. The model identification procedure and its use are demonstrated on the example of a particular panel. A detailed methodology for application is presented for users of the MATLAB environment.*

Keywords

Photovoltaic panel, identification, modeling, MATLAB.

1. Introduction

The share of photovoltaic power in total electricity production continually increases. These renewable energy sources often consist of many hundreds or thousands of photovoltaic panels. The panels are made up of dozens of basic photovoltaic cells, usually connected in series for higher output voltage. Also from the technical point of view, quite lot of attention is given to the problem. Research teams deal with both technology research, and measurement and creation of standards (in the Czech Republic, for example, ČSN EN 60904-1, ed. 2, ČSN EN 60891, ed. 2). We will not repeat already known information. The issue is abundantly published, see e.g. [1-6], [11] and the Internet.

This article describes the original method for the mathematical model of a photovoltaic panel (PV) for a given temperature. Knowledge of such a model is very important for quality of computer experiments, design and optimization [1], [7], [10], [14], [15]. For the supply of a.c. loads, the operating points of panels are regulated by converters in order to deliver maximum available power (Maximum Power Point Tracker – MPPT method), see [2 to 6], [8] [9], [12], [13]. The proposed method is consistently based on the measured output $i = f(v)$

characteristics for given solar irradiation. The essence of the approximation task is the simplified Shockley's equation and consistent nonlinear and parametric correction of power losses within the panel. The output is a particular mathematical model with very good agreement with measured data. The model identification algorithm is programmed in MATLAB [16]. The article also includes the analysis of approximation errors and their sources.

2. Basic Idea of Approximation

Modeling of photovoltaic cells is based on the well-known Shockley's equation. Its simplification and moving to the 1st quadrant gives us the function:

$$i = I_k - I_0 . \exp\left(\frac{v}{V_T}\right) \qquad (1)$$

where I_0 is a current through a photodiode in reverse direction, V_T is thermal voltage, and I_k is a short-circuit current which depends on the irradiation q. Simplification of equation (1) causes an error, which, however, does not exceed 0.1% [17].
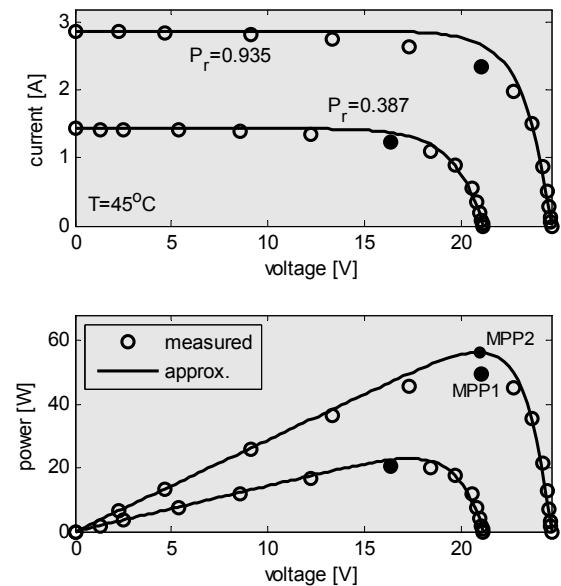

Fig. 1. Approximation of measured data.

As mentioned above, equation (1) well approximates the progress of $i = f(v)$ characteristic of one ideal photovoltaic cell. Fig. 1 shows the application of (1) to entire

photovoltaic panel which is operated in our department. It consists of 36 cells connected in series. Concrete values of P_{mpp1} and P_{mpp2} were obtained from lower graph in Fig. 1 (measured and simulated powers in MPP point).

A simple multiplication of voltage by 36 obviously does not provide good results. The reason is the existence of a number of resistance losses in each cell. Their measurement is more complicated and often technically impossible in practice. The panel under test has nominal power P_n= 53 W. In Fig. 1, there are two irradiations q [Wm^{-2}] used as a parameter. We will distinguish the curves by relative power P_r= P_{mpp}/P_n[-] instead of solar irradiation. It is more practical way, with regard to measuring. Fig. 1 clearly shows the dependence of the approximation error, which is the largest around MPP maximum power points. It is clear that power loss ΔP is distributed along the axis of voltage, nonlinear and parametrically: $\Delta P = f(v, P_r)$. For example in case of the upper power curves, the following was found: P_{mpp1}= 49.4230 W and P_{mpp2}= 56.3153 W. Then, it is possible to calculate the absolute and the relative power error P_{mpp}: $\Delta P_{mpp}= P_{mpp2} - P_{mpp1}$= 6.8924 W, $\delta P_{mpp}= 100\Delta P_{mpp}/P_{mpp1}$= 13.95 %. For the voltages other than v_{mpp} and other relative powers P_r there are different values, of course. The curve of absolute errors in the measured points is shown in Fig. 2. The curves are not normalized to maintain the visual similarity with Fig. 1.
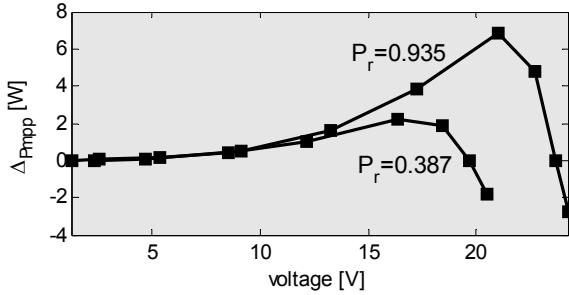

Fig. 2. Absolute power error along the voltage axis.

If the entire photovoltaic panel is at disposal, it is more suitable to approach the approximations from above which means to begin with practical measuring. On the basis of their results, the automatic approximation system is built. Its output is then a functional model with sufficiently small deviations from the measured data. The basic idea of the described approach is in maintaining of the positive approximation dependence of the equation (1), and in nonlinear and parametrical correction of current and power on the basis of the measured data. It implies the main approximation method strategy:

$$i_{fin} = i - i_{corr}, \quad i_{corr} = v.i.K_{corr} \qquad (2)$$

where i_{corr} is the nonlinear and parametrical correction of the basic characteristic. From this it can be deduced:

$$K_{corr} = \frac{\Delta P_{mpp}}{P_{mpp}} \cdot \frac{1}{v_{mpp}} \qquad (3)$$

where ΔP_{mpp} is an absolute error of the maximum power for given P_r, v_{mpp} is voltage in the maximum power point.

The first term of (3) is then the maximum power relative error. By comparing equations (1), (2) and (3), we can write down the final approximation equation of the whole method:

$$i_{fin} = \left[I_k - I_0.\exp\left(\frac{v}{V_T}\right) \right].(1 - v.K_{corr}). \qquad (4)$$

The approximation application leads to determination of the vector $c_{appr}[I_k, I_0, V_T, K_{corr}]$ for the particular panel, relative power P_r and temperature. The approximation task system, which we designed, then consists of these steps:

- The $i = f(v, P_r)$ characteristic measurement for a particular panel and several irradiations, or relative powers.
- Automatic determination of partial approximation dependences.
- Automatic identification of the entire panel model.

2.1 Photovoltaic Panel Model Identification

As was mentioned before, the basic assumption is a series of measured $i = f(v, P_r)$ characteristics for several relative P_r powers.
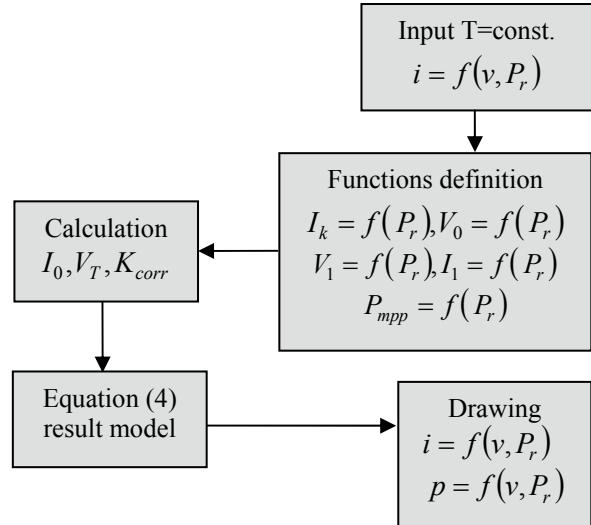

Fig. 3. Identification of model from the measured data.

These data are prepared as an output matrix of the entire system. To create a global panel model, it is necessary to identify the system. In our case, it means to determine the approximation equations I_k, I_0, P_{mpp}, V_1, $I_1 = f(P_r)$ according to section 3.3 and Fig. 6. The $[V_1, I_1]$ coordinates determine the point on the basic characteristic behind the *MPP* point for the correct determination of the equation (1); see (5), (6) and [17]. The user then appoints only the P_r relative power for which the approximation is to be used.

All the equations mentioned above are automatically calculated by the system without interferences by the user, see Fig. 6. The measured data are sufficient for it. If the equations are known, the system then creates the general model of the panel in agreement with (4), which means that

it calculates the I_k, I_0, V_T, K_{corr} constants. Thus, the power losses along the voltage axis are effectively corrected. The whole progress is shown in Fig. 3.

Finding the equations mentioned above and the constants is necessary for the correct application of (4). The panel is explicitly identified by this process. As can be seen below, most of the partial equations are parabolas, see Fig. 6. Their identification explicitly defines a particular photovoltaic panel.

3. Illustrative Example

In our department, we operate two photovoltaic systems. As we mentioned before, one of them is a panel with the nominal power $P_n = 53$ W. It consists of 36 cells connected in series, see Fig. 4.
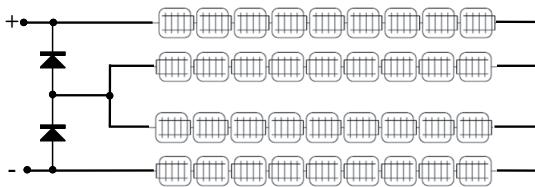

Fig. 4. Approximated panel topology.

Each cell has approximately the following parameters: $V_{01} = 0.535$ V, $I_{k1} = 0.544$ A by the temperature $T = 45°C$ and for the given relative power.

3.1 Measured Data

In agreement with previous reading, we measured a network of $i = f(v, P_r)$, $T = const.$ characteristics, see Fig. 5. The number of measured values – 15 – is relatively low. We want to prove that also in this case the approximation system provides fully usable results.
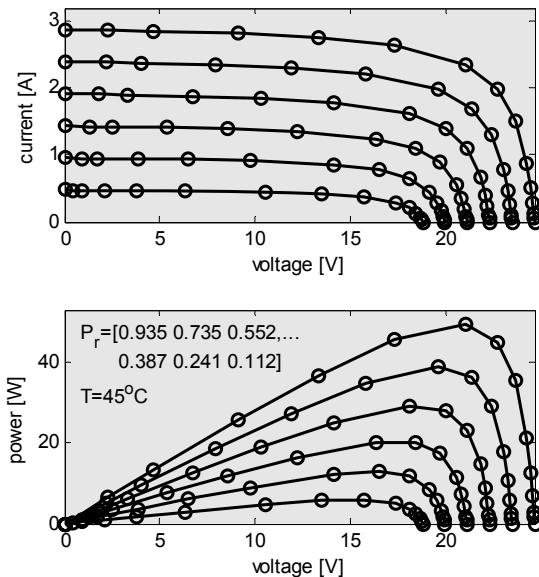

Fig. 5. Measured $i, p = f(v, P_r)$ characteristic for the panel $P_n = 53$ W.

3.2 Partial Functions Definition

In agreement with previous reading, the system now calculates the basic equations I_k, V_0, P_{mpp}, V_1, $I_1 = f(P_r)$, see Fig. 3. The results are shown in Fig. 6. Displayed points were measured and interpolated by using quadratic equations because of the smallest approximation errors. The dependences are necessary for the correct definition of I_k, I_0, V_T, K_{corr} constants in (4). Let us emphasize that the equation is not applied on a cell, but on the entire panel. That is the main difference from the other approaches.

The equations for each function are automatically generated by the system. We limited the number of the displayed decimal place in order to save space. The presented outputs are valid for a particular measured panel and its temperature.

3.3 Entire Model Identification

If the dependences according to Fig. 6 are known, then for the known irradiation q, or the P_r relative power, these needed constants can be defined including the one in equation (3):

$$I_0 = \exp\left[\frac{V_0 \cdot \ln(I_k - I_1) - V_1 \cdot \ln I_k}{V_0 - V_1}\right], \tag{5}$$

$$V_T = \frac{V_1 - V_0}{\ln\left(\frac{I_k - I_1}{I_k}\right)}. \tag{6}$$

The derivation of the equations was published e.g. in [17] for the constant temperature.
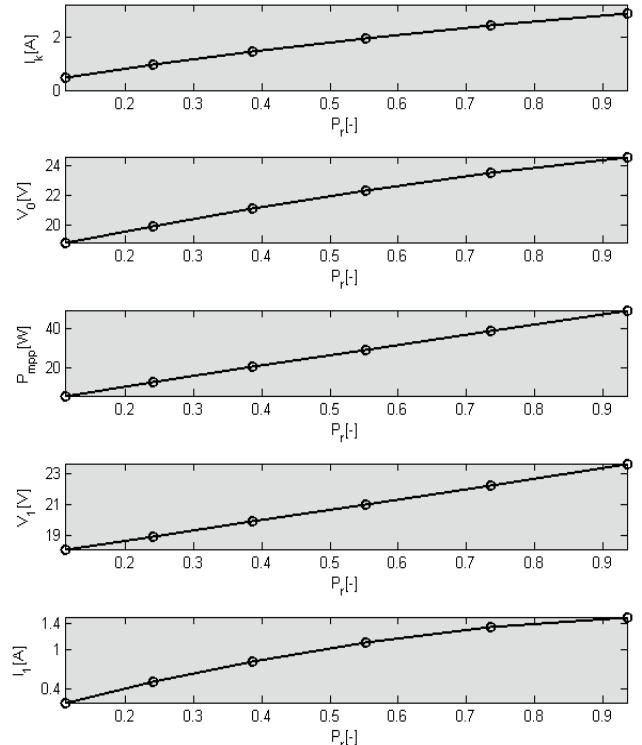

Fig. 6. Fragmentary equations definition for the panel description.

The vector of the independent variable is defined on the interval: $v \in \langle 0; V_0 \rangle$ for each relative power.
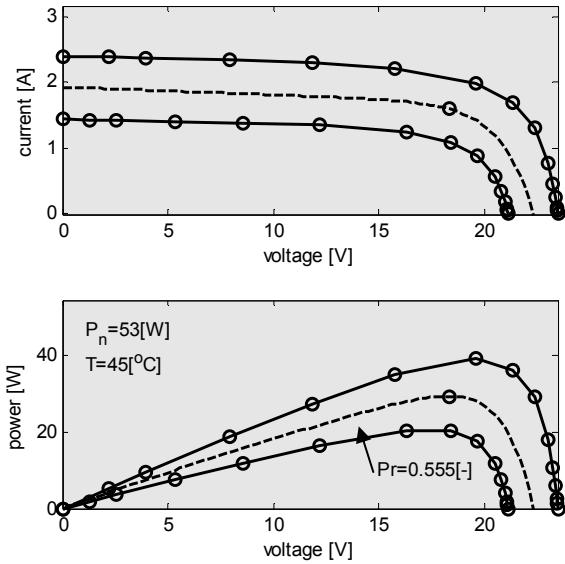

Fig. 7. Approximated dependences for $P_r = 0.555$ [-].

As it was mentioned, the system tends to define the I_k, V_T, I_0, K_{corr} constants for the application of (4). It is the final model of the particular photovoltaic panel for the given temperature. For example, in case of constant power $P_r = 0.555$ [-] the constants are as follows: $I_k = 1.930$ A, $V_0 = 22.335$ V, $P_{mpp} = 29.265$ W, $I_0 = 6.589 \cdot 10^{-7}$ A, $V_T = 1.500$ V, $K_{corr} = 6.072 \cdot 10^{-3}$ V^{-1}.

Fig. 7 shows a new-drawn final approximation of the characteristic for the calculated constants (red). The analytical version of the equation is in Fig. 8 at the bottom.

The calculated I_k, I_0, V_0, K_{corr} constants are then put to (4) and the functions of $i = f(v, P_r)$ and $p = f(v, P_r)$ are drawn. These target constants are determined by a particular panel and temperature.

We designed an application in the MATLAB system, with the working title *Photovoltaic_Model_01*. It consists of about 280 lines in a single script. The application is autonomous; it requires only a network of measured characteristics according to Fig. 5 and defined P_r relative power. Its output are the above mentioned constants for each irradiation, or P_r. Except that, it produces a number of textual information, for example, the particular form of fragmentary equations and the final approximation function, see Fig. 8.

The output text information is quite extensive and carefully formatted by *sprintf* command. The user defines only the irradiation, or the relative power. Except for that, the user can also define the value of the panel load R_L and observe its coordinates on the appropriate characteristics. The system leads the user by presenting of the real load limits.

Fig. 9 shows the network of panel characteristics approximated by the described system.

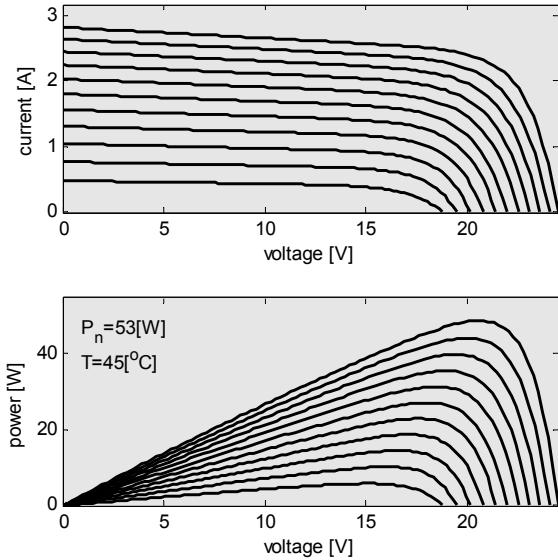**Fig.8.** Partial textual transcript of the *Photovoltaic_Model_01* application.

Fig. 9. Approximated panel characteristics network.

3.4 Approximation Errors Evaluation

In connection with the approximation method described above, it is necessary to answer two questions about approximation errors, particularly their limits:

- Main error sources identification.
- General approximation error limits evaluation.

The potential sources of errors can be the simplification of the equation (1) discussed in section 2, and the accuracy of the fragmentary I_k, I_0, P_{mpp}, V_1, $I_1 = f(P_r)$ equations identification that leads to the general model establishment. The error is not caused by final accuracy of basic characteristics measurements because the described method approximates the input data whether they are credible or not. When calculating, the program works with *double precision* full data accuracy. We will not present theoretical considerations about uncertainty. Instead, we present Fig. 10, which shows a relative error of the function of $\delta_P = f(v)$, $P_r = 0.9349$ [-]. In the upper graph, there is comparison of both measured and approximated dependences. It can be said that the relative error did not exceeded $|\delta_P| \leq 0.12$ [-]. Given that this limit was calculated for the largest relative power of the entire panel (measurement), this limit can be seen as potentially the greatest relative deviation approximation method. This boundary includes all the influences on accuracy. For smaller values of P_r the error is always smaller. We believe that these results fully demonstrate the applicability of the described approximation method.

The largest error occurs around the open-circuit voltage, however, near the P_{mpp} power it approaches zero. This argument is important with regard to the working point of photovoltaic panels in practice, when the transducers seek to keep output power close to maximum.
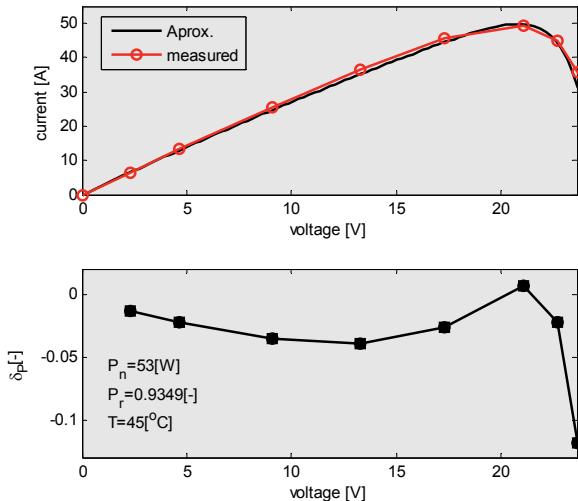

Fig.10. Approximation relative error evaluation.

4. Conclusion

The article presets the original method of approximation of $i = f(v, P_r)$ and $p = f(v, P_r)$ photovoltaic panel characteristic and one particular temperature. The input values are measured $i = f(v, P_r)$ characteristics and particular value of P_r relative power. The output is a mathematical model of a particular panel. The advantages of this method are the orientation on the practical measurements and minimal

approximation error in P_{mpp} points. The approximation application was created in the MATLAB environment and consists of a single script. The entire system was tested with practical experiments in our department.

Acknowledgements

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