

Behavioral Model of Photovoltaic Panel in Simulink[®]

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Abstract—This article deals with creation and application of a model of photovoltaic panel in the MATLAB[®]&Simulink[®] environments. An original model of the real PV panel is applied using the model based design technique. A so-called physical model is also developed using the SimPowerSystems[™] library. The described PV panel model is applied for maximum power optimization in the one-shot and the continuous modes. A few illustrating examples and source code parts are also presented.

Index Terms—solar panel, behavioral model, Matlab.

I. INTRODUCTION

Photovoltaic panels (hereafter PV) are more still widespread source of electricity. For the purposes of computer simulations, it is useful to have an accurate model. Many articles on the topic of modeling of the PV panels were published. Many, however, deal only with the basic photovoltaic cells [1], [2], [3]. The course of $i = f(v)$ cell characteristic is usually approximated by Shockley's equation. This equation is able to model the ideal cell behavior sufficiently.

Photovoltaic power stations contain many hundreds of PV panels, which consist of dozens of cells, normally connected in series. Direct application of Shockley's equations for the entire panel does not bring good results. This is due to the existence of power losses, which is spread out along the voltage, non-linearly and parametrically.

In [4], we published the original method of real PV panel model identification. It is done consistently on the basis of the measured $i = f(v)$ characteristic for several different solar irradiances. In the next section, we briefly summarize the basic process of modeling. Our original contribution is the application of the identified models in the Simulink environment [5], [6]. The result is a functional dynamic model that accurately corresponds to the measured data. The model serves as a basis for creating the so-called physical model using the library *SimPowerSystems*[™]. The model is valid for one specific panel and one particular temperature.

Figure 1 shows the topology of PV panel which we operate in our department and which will serve as a testing panel. It consists of 36 series-connected basic cells and has a nominal output power $P_n = 53 \text{ W}$.

Figure 2 shows the measured $i = f(v)$ characteristics for a total of six $q [W.m^{-2}]$ solar irradiances. Instead of solar irradiation, we distinguish the graphs with a relative power

$P_r = \frac{P_{mpp}}{P_n}$ [-]. It is more practical way, regarding both the

measuring process and the computer simulations. The courses were obtained at the temperature $T = 45^\circ\text{C}$.

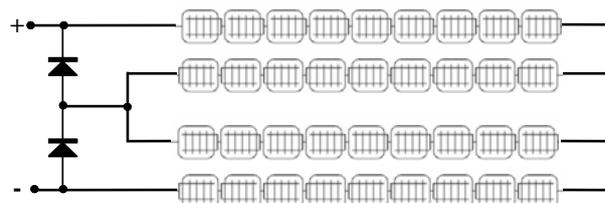


Figure 1. Testing PV panel topology

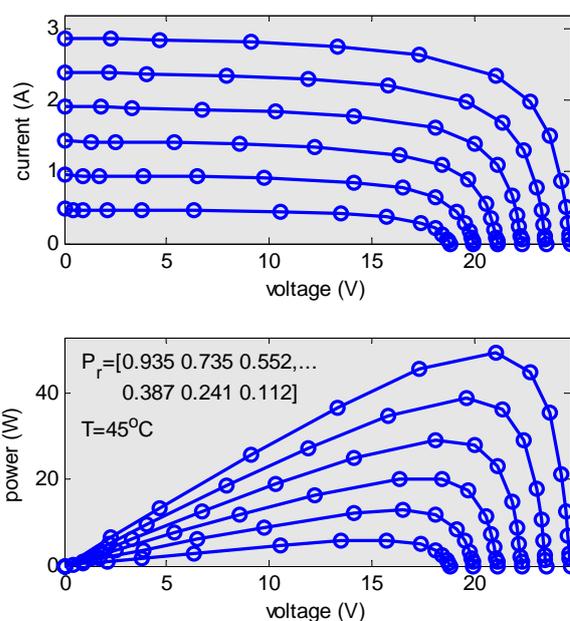


Figure 2. The $i = f(v, P_r)$ measured characteristics for the panel $P_n = 53 \text{ W}$

II. ENTIRE PANEL MODEL IDENTIFICATION

As mentioned above, the Shockley's equation cannot be applied directly to the entire panel, however it has a very strong potential for the model creation. The Figure 3 shows a large approximation error in case the Shockley's equation is applied to the entire panel without the further treatment. The largest error arises in the vicinity of the P_{mpp} maximum power, see the *MPP1* and points [7]-[18]. These statements are very important especially in practical operating because real photovoltaic systems works round the maximum output power [19]-[26].

In order to apply the equation to the entire PV panel, it is necessary to make the correction of the current and power. The correction has to be nonlinear and parametrical due to the solar irradiation and the P_r relative power.

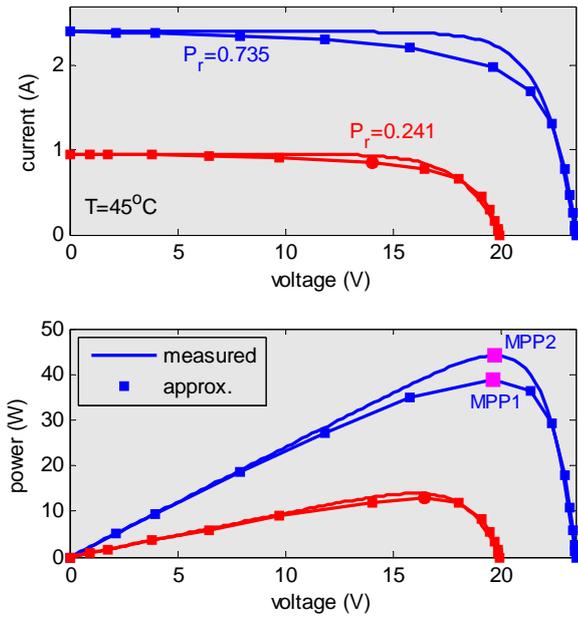


Figure 3. Measured data approximation by the equation (1) application

The final approximation equation is:

$$i = \left[I_k - I_o \cdot \exp\left(\frac{v}{V_T}\right) \right] \cdot (1 - v \cdot K_{corr}) \quad (1)$$

where I_k is a short-circuit current, I_o is a photodiode reverse current, V_T is a temperature voltage and K_{corr} is a correction variable.

For the K_{corr} correction coefficient applies this:

$$K_{corr} = \frac{\Delta P_{mpp}}{P_{mpp}} \cdot \frac{1}{v_{mpp}} [V^{-1}], \quad (2)$$

where ΔP_{mpp} is course of an absolute error of P_{mpp} power. In [4], we described the MATLAB system application which on the base of measuring identifies the K_{corr} value automatically for each P_r relative power. For example, for $P_r = 0.600 [-]$ the approximation function (1) is as follows:

$$i = \left(2.01 - 6.64 \cdot 10^{-7} \cdot \exp\left(\frac{v}{1.52}\right) \right) \cdot (1 - v \cdot 6.02 \cdot 10^{-3}). \quad (3)$$

The application mentioned above therefore leads to the definition of a vector $v_{appr} [I_k, I_o, V_T, K_{corr}]$ for given P_r and the temperature. The calculated values are valid for one particular panel. The Figure 4 shows the approximated courses $i = f(v, P_r)$ and $p = f(v, P_r)$ just for $P_r = 0.600 [-]$.

One of the application outputs is also equations that identify the PV panel, especially the $I_k, I_o, P_{mpp}, V_T, I_1 = f(P_r)$ equations. The $[V_T, I_1]$ coordinates determine the basic characteristic point behind the MPP in order to determine the equation (1) accurately. The user then enters only a particular P_r relative power, for which the approximation is to be used. All the equations mentioned above are calculated by the system without the user's intervention. The measured data are fully sufficient. As mentioned above, the computer algorithm works with one concrete operational temperature.

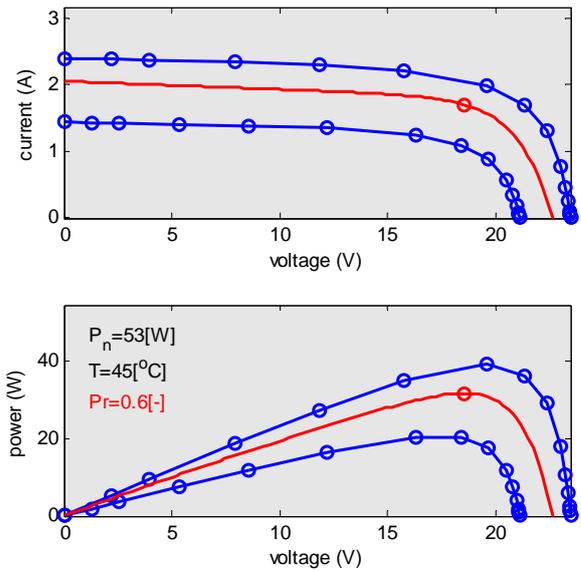


Figure 4. Approximated courses for $P_r = 0.600 [-]$

When the equations are known, the system then creates the entire panel model in agreement with the equation (1), ergo, it calculates the I_o, V_T, K_{corr} constants. Thus the effective correction of the power losses along the voltage axis is done for $P_r = 0.600 [-]$.

The analytical form of equations in Figure 5 is very important. These equations clearly identify the panel and are the basis for the circuit model, see below.

```

Command Window
New to MATLAB? Watch this Video, see Demos, or read Getting Started.

ans =

Curves: Ik,V0,Pmpp,V1,I1,PalmaxXro,DPmpp=f(Pr)
-----
Ik=-0.953915.Pr^2+3.894431.Pr+0.062597
V0=-2.336770.Pr^2+9.532388.Pr+17.764035
Pmpp=6.556171e-014.Pr^2+5.300000e+001.Pr+1.521507e-014
V1=0.320534.Pr^2+6.441230.Pr+17.381191
I1=-1.277825.Pr^2+2.926142.Pr-0.122493
PalmaxXro=563.868446.Pr^2+719.941515.Pr+22.467143
DPmpp=3.355934.Pr^2+3.617963.Pr+0.575589

ans =

Final approximation:
i=( 2.056-6.641e-007*exp(u/ 1.515) ).(1-u*6.015e-003)
    
```

Figure 5. Panel identification equations in analytical form

III. MODEL IN SIMULINK ENVIRONMENT

The MATLAB extension called Simulink is entitled to appropriate design and simulation of dynamic systems in a general block form. The user works with so-called mode-based design technique. He drags the blocks from the library to the model window and connects them according to the logic of the work. The work includes also setting of some parameters, e.g. the simulation time, numerical method type for calculation (ODE solver) etc. Simulink is fairly intuitive, but it also offers advanced modes of operation. Except the block mode, it is possible to create the so-called physical models with blocks from various technical fields (electronics, hydraulics etc.). Libraries in this case offer also the basic components of the given field.

Classic Dynamic Model

As mentioned before, it is necessary to select the needed blocks from the library and to connect them. The Figure 6 shows the block scheme of the model. The input variables are P_r relative power and the source of variable voltage V_{in} which us used for drawing the $i, p = f(v)$ characteristics.

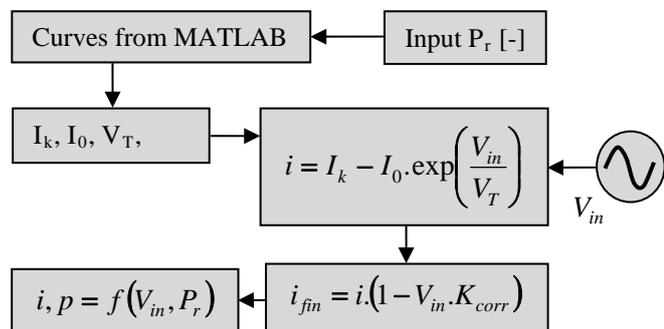


Figure 6. Dynamic model creation process in Simulink

The Figure 7 shows the total dynamic model of the PV panel. It is built according to the scheme in Figure 6. The orange blocks are the identification of the panel; the green blocks contain the required equations. The blue blocks are the numerical outputs of main variables.

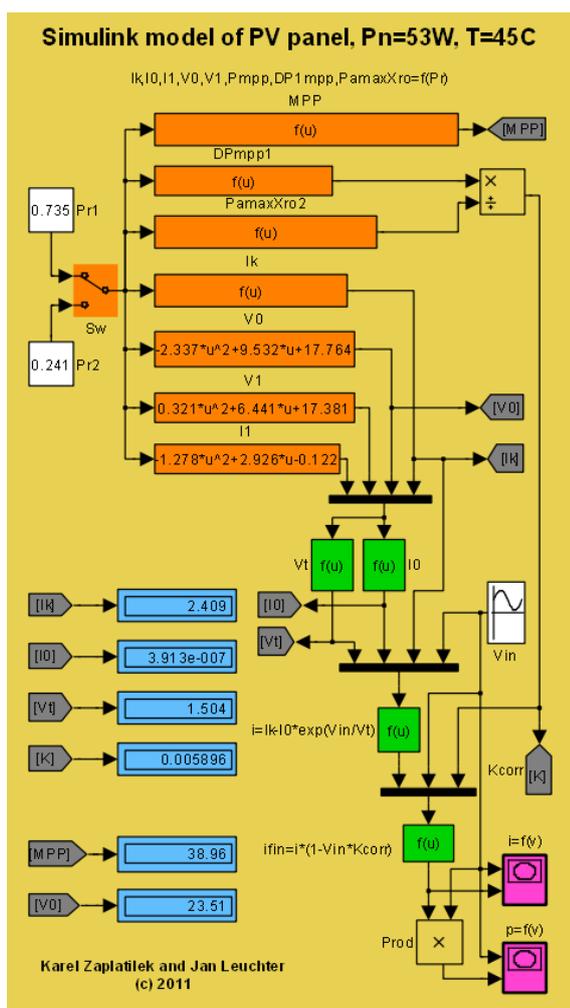


Figure 7. Final PV panel model in Simulink

The model also comprises a system of equations according to Figure 5 that determines the given PV panel.

Subsequently, the I_k, I_0, V_T, K_{corr} constants are calculated. They are the basis for the calculation of the current according to the equation (1). Then the required courses are drawn.

The Figure 8 shows the input courses after the simulation start. The Sw manual switch serves to rapid changes of solar irradiation in the form of a relative power.

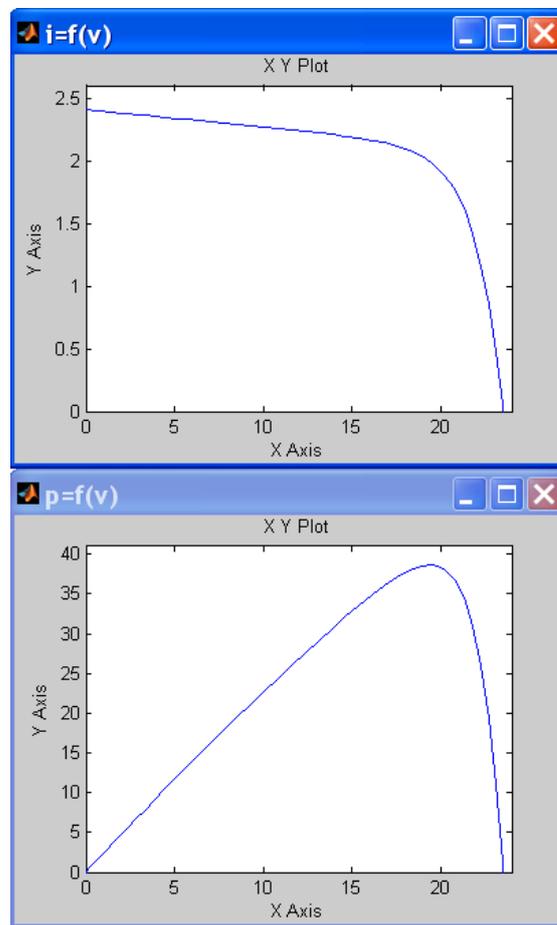


Figure 8. The $i = f(v)$ and $P = f(v)$ characteristics simulation

The advantage of the classic model is its clearness and simplicity of its building. However, it does not enable the circuit approach to the PV panel. In practice, the circuit approach is often requested. For its build or supplement, it is necessary to create a so-called physical model. The user has to respect some of the differences.

In case of more common work with the PV panel, it is more comfortable to create a subsystem of the entire panel. The orange blocks in Figure 7 are integrated into a single block. The user can edit its sign, description, etc. The Figure 9 shows the model from Figure 7, where the panel is displayed as a subsystem. It depends on user, which of the block can be included, however the orange colored equations from Figure 7 are always included. The subsystem inner structure can be displayed by Ctrl-M command. The simulation results are identical with Figure 8. It is obvious that the panel can be excited with a DC instead of AC voltage. In that case the violet blocks are not relevant.

The physical model is appropriate when the circuit approach to the problem is required. There are a few specialties how to draw the physical model.

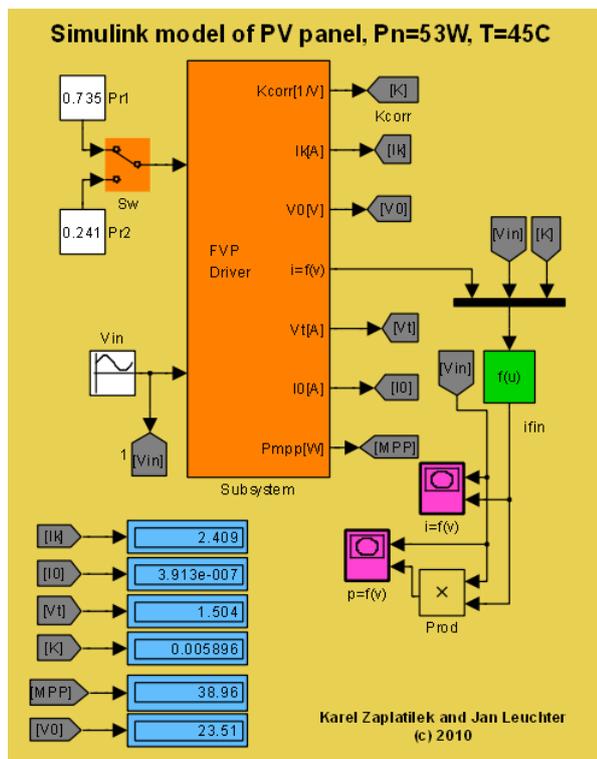


Figure 9. PV panel model as a subsystem

The user can select the basic electronic components from the library. Some of the special blocks such as current and voltage measurement are also used.

The Figure 10 shows the physical PV panel model which uses the model constants from the Figure 9. The main block is a controlled current source - *CC source*, which is excited by the current from the $i = f(v)$ block. The excitation block is programmed by the equation (1) with specific values of the constants, see above. The panel load is formed by a RL resistor. The current and voltage output is formed by the measurement blocks. The actual power and load values are calculated by the multiplication and division blocks. The blocks are from the SimPowerSystems™ library.

Functional physical model is the basis for further experiments, for instance with dc-dc converters, optimization, etc. At recent time, the special libraries mentioned above are supplemented with new elements and options. In general, the physical modeling is advantageous in terms of connecting the blocks of different fields, as mentioned above. The user does not have to use the general term “signal”, but specific variables (current, voltage, temperature, pressure, etc.). The transfer is performed by the presented and other special blocks. A great advantage of the PV panel model implementation is also the ability to operate the model from MATLAB environment, or to create separate operating m-files.

In the case of the work with another panel, the equations have to be reset in the window in Figure 7, or the subsystem contents. The other parts of the model remain intact. Used inner mathematical models are relatively simple and idealized. Nevertheless, the physical models are usable also for more extensive systems including the photovoltaic ones. When the physical model is created then all classical Simulink signal and system blocks are applicable too. It is big advantage in case of such modeling.

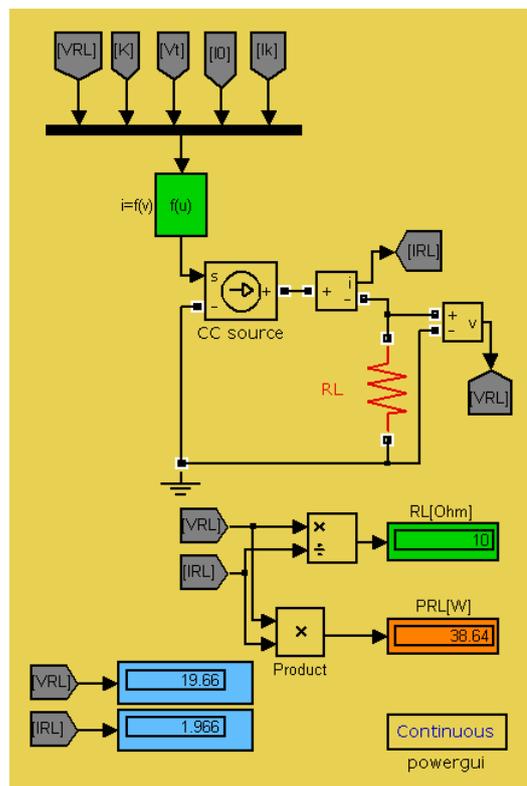


Figure 10. PV panel physical model

IV. POWER OPTIMIZATION

A main operating point of the PV panel is a maximum output power (MPPT). To provide this condition means to create a power optimization algorithm. The block diagram of the technique is shown in Figure 11. It is a classic one-dimensional iteration algorithm based on splitting interval. The user can especially define an arbitrary initial value of load resistance. The algorithm uses an intelligent stepping control. Optionally, the optimization loop can work continuously. In that case the system continually sweeps an optimal operating point. If the operating point changes its position (solar irradiation, temperature, wear) then optimization system will set the optimal conditions immediately.

The described optimization algorithm is launched by using a so-called *callback technique* thanks to the model block *Optimization*, see Figure 12. There is a special m-file with an optimization source code.

The system will find the power maximum during 7 to 9 iterations according to user’s defined accuracy. The graph shows an optimization trajectory. It is evident that the used optimization algorithm is convergent and sufficiently fast.

The optimization system will find the power maximum, see Figure 9. The main advantage of the described technique is its independence on a concrete cause of the operating point changes. In practice, the PV panel load is most often a dc-dc converter. In that case the electric current is the main optimization variable instead of PV panel load resistance. In our department, we use an automated measuring workstation in connection with described optimization system. All of our developed models and algorithms were verified by performing many practical experiments. All our real experiments are based on long-term evaluation of the measured results.

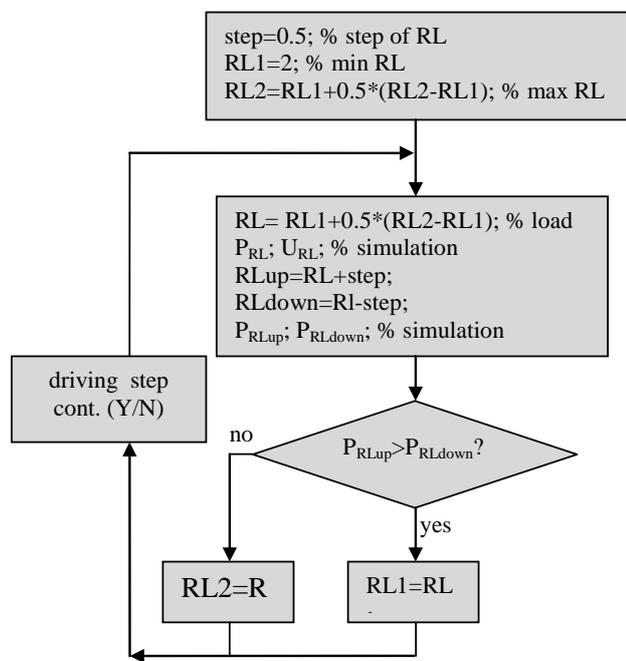


Figure 11. Block diagram of power optimization system

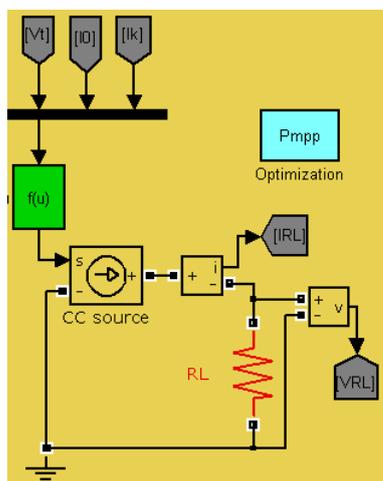


Figure 12. Power optimization callback block

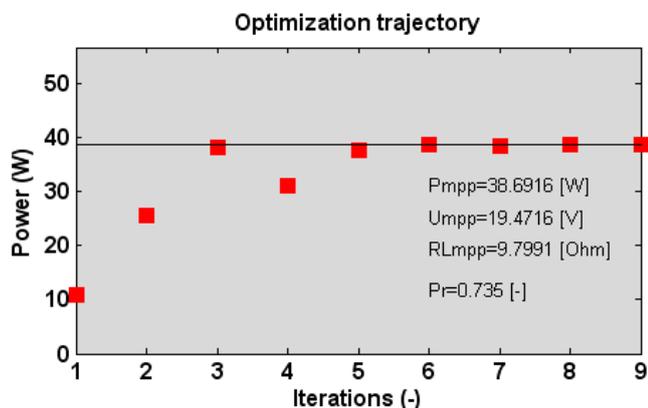


Figure 13. Power optimization result

The Figure 14 shows a part of the optimization m-file mentioned above. There are two important MATLAB commands *bdroot* and *set_param* for the model control. The user can control his Simulink models very effectively from the common MATLAB workspace.

```

%-----
Model=bdroot(gcf); % model name
set_param([Model, '/', 'RL'], 'Value', num2str(RLdown));
set_param(Model, 'Simulationcommand', 'Start') % start
    
```

Figure 14. Part of optimization m-file (callback)

A path to the m-file is set within the *Optimization* model block thanks to the model menu *Edit/Block properties.../Callbacks/OpenFcn*. The described system connects the main MATLAB and the Simulink environments.

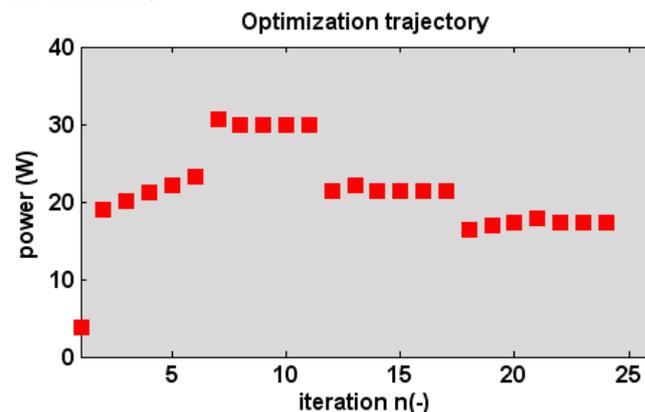


Figure 15. Continuous power optimization

In the case of continuous power optimization, the system continuously looks for the power maximum. The Figure 15 shows the described regulation for several solar irradiation changes. It is the typical power maximum continuous look. The system is robust and fast. An optimal PV panel operational mode is set by using the system independently of any changes.

V. CONCLUSION

In this article the procedure for creation of the photovoltaic panel model in the Simulink environment is introduced. The model is valid for a specific panel and a given temperature. The solar irradiation is operated by the change of the P_r [-] relative power. The classic model in Simulink, supplemented with so-called entire panel subsystem, is then created. Except of that, the physical model using the specific circuit elements is also created. It enables to perform the electric circuit level experiment using, for instance, the dc-dc converters. The advantage of this method is the very close agreement of the model with the measured data from which the method is based on. The possibility of external operating with m-files in MATLAB offers many more options. All presented algorithms and results are based on long-term automatic measurement of the real photovoltaic panels in our department. Embedded PV panel models in MATLAB & Simulink extend current possibilities of the system.

ACKNOWLEDGMENTS

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