Finite State Machine Model of photovoltaic panel

Michal Baherník, Marek Höger, Peter Braciník, Martina Látková
University of Zilina, Faculty of Electrical Engineering, Department of Power Electrical Systems, Slovakia
michal.bahernik@kves.uniza, marek.hoger@kves.uniza, peter.bracinik@kves.uniza, martina.latkova@kves.uniza,

This paper deals with a mathematical model of a photovoltaic panel, based on finite state machine, which directly supplies a constant resistive load without inverter cooperation. The model's correctness is evaluated through the comparison of simulated values and real measured data.

Matematical model of a PV cell

The equivalent circuit of solar cell based on Shockley equation is shown on Fig. 1. This model consists from a current source, a diode, a shunt resistance R_{SH} and a series resistance R_S, which represents an internal resistance of the cell. In this paper, it is considered that the solar cell is loaded by known resistive load.

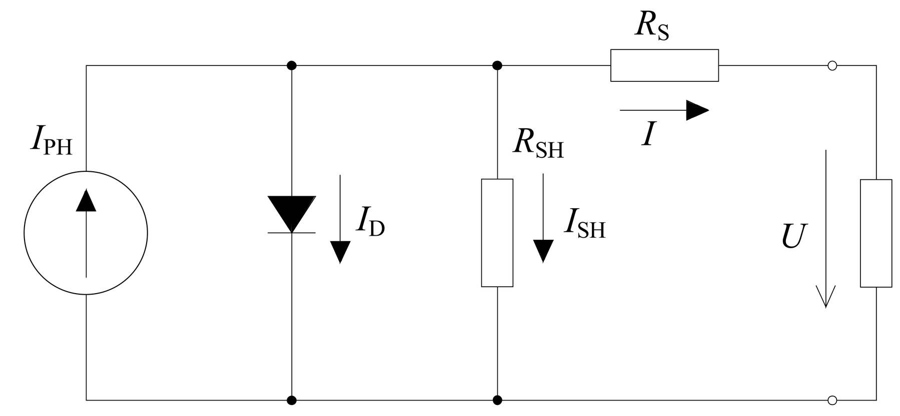


Fig. 1. Equivalent model of a photovoltaic cell with resistive load

Current-voltage characteristic (I-V curve) of a solar cell is a nonlinear function, therefore its mathematical model is also nonlinear and it's necessary to use iterative methods (e.g. Newton's iterative method) to solve the model. We can solve the nonlinear system using Newton-Raphson iterative method:

$$U_D^{(k+1)} = U_D^{(k)} - \frac{f_{(U_D^{(k)})}}{f'_{(U_D^{(k)})}}. \tag{1}$$

As it can be seen on Fig. 2, the I-V curve has no local extremes. Therefore, gradient based methods, like Newton-Raphson, are unable to find the solution of such an equation. This can be solved by modifying the original equation to a quadratic form. This alternated equation has the same solution as the original function, but now the solution is located in a local minimum of the function (Fig. 2).

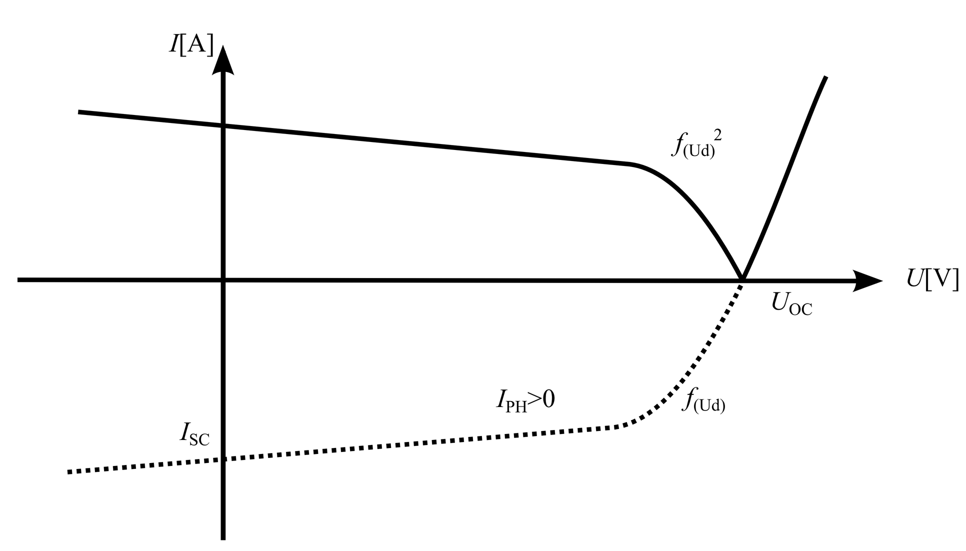


Fig. 2. The quadratic form of I-V curve

The quadratic form is

$$f_{(U_D)} = (U_D - (I_{PH} - I_s \cdot e^{K_E \cdot U_D}) \cdot K_R)^2 \tag{2}$$

and its first derivation is

$$f'_{U_D} = 2\cdot(K_R + I_S \cdot K_E \cdot e^{K_E \cdot U_D} + 1)\cdot(U_D - I_{PH} + K_R \cdot U_D + I_S \cdot e^{K_E \cdot U_D}). \tag{3}$$

Equation (3) changes all negative values to positive ones (Fig. 2) and so the function can be solved using the Newton-Raphson iterative method. After knowing the solution – the value of diode voltage U_D, it is possible to calculate the values of all other variables.

Finite state machine model of PV panel

Equations (2) and (3), as well as equations from [1], were used to create a model of PV panel in software tool Ptolemy II [2] (Fig. 3). In order to implement its mathematical description, a FSM model was created (Fig. 4).

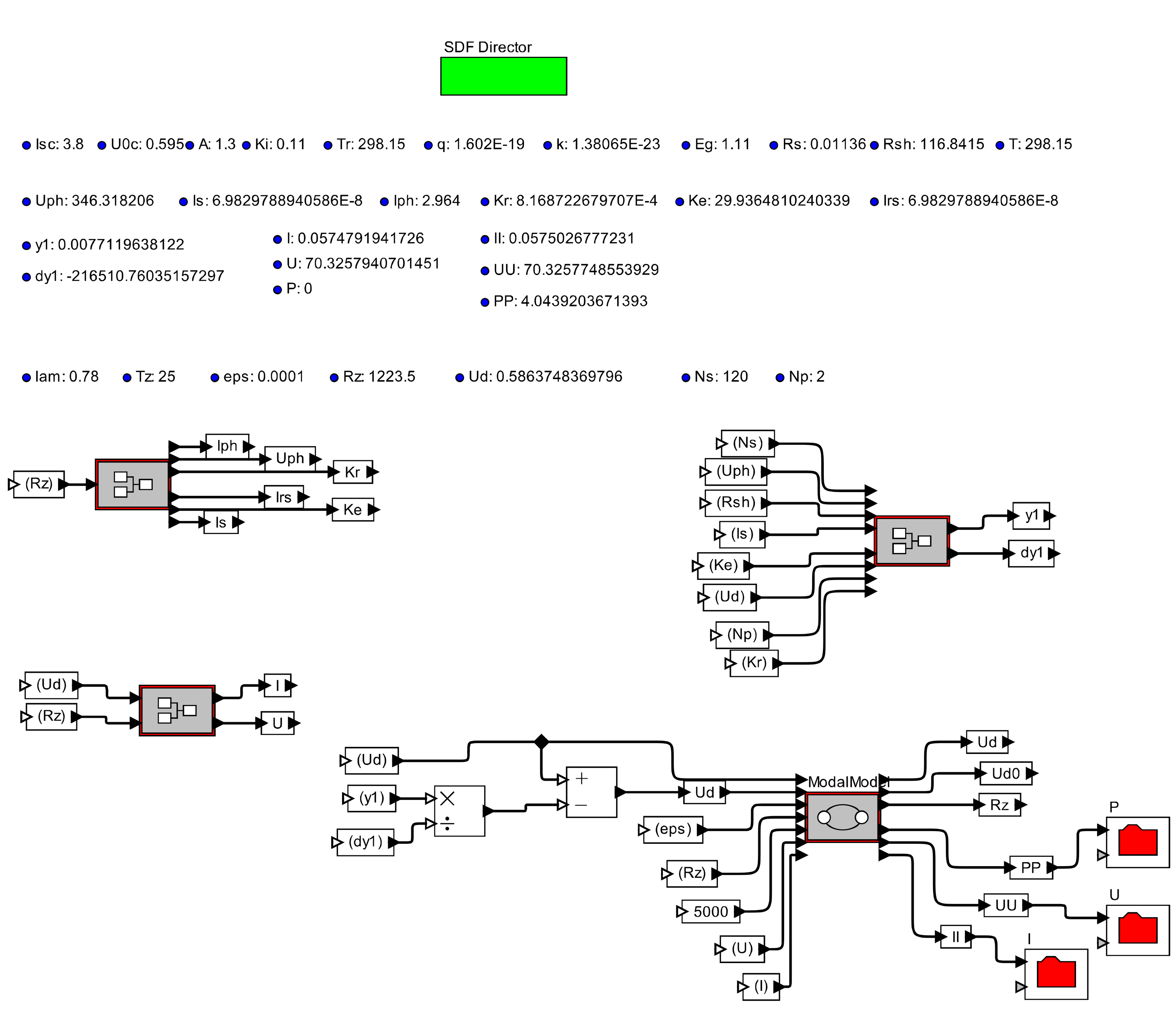


Fig. 3. Model of a PV panel created in Ptolemy II

The FSM model consists of 4 *states* (Fig. 4). Simulation begins in the initial "*state*", in which an estimated value U_D (its value is represented by the input parameter "old" in Fig. 4) is saved to an auxiliary variable U_{D0} (expressed as Ud0 in Fig. 4). In the next state, "*state2*", a condition is tested, if the absolute difference between the new and old calculated value of U_{D0} is less than the given error *eps*. If the result of this comparison is logical "false", the new value of diode voltage is written to U_{D0} and the calculation is repeated (the next iteration is calculated). If the result is "yes", the last value of U_{D0} can be considered as the correct one and it is assigned to the variable U_D (expressed as Ud in Fig. 4).

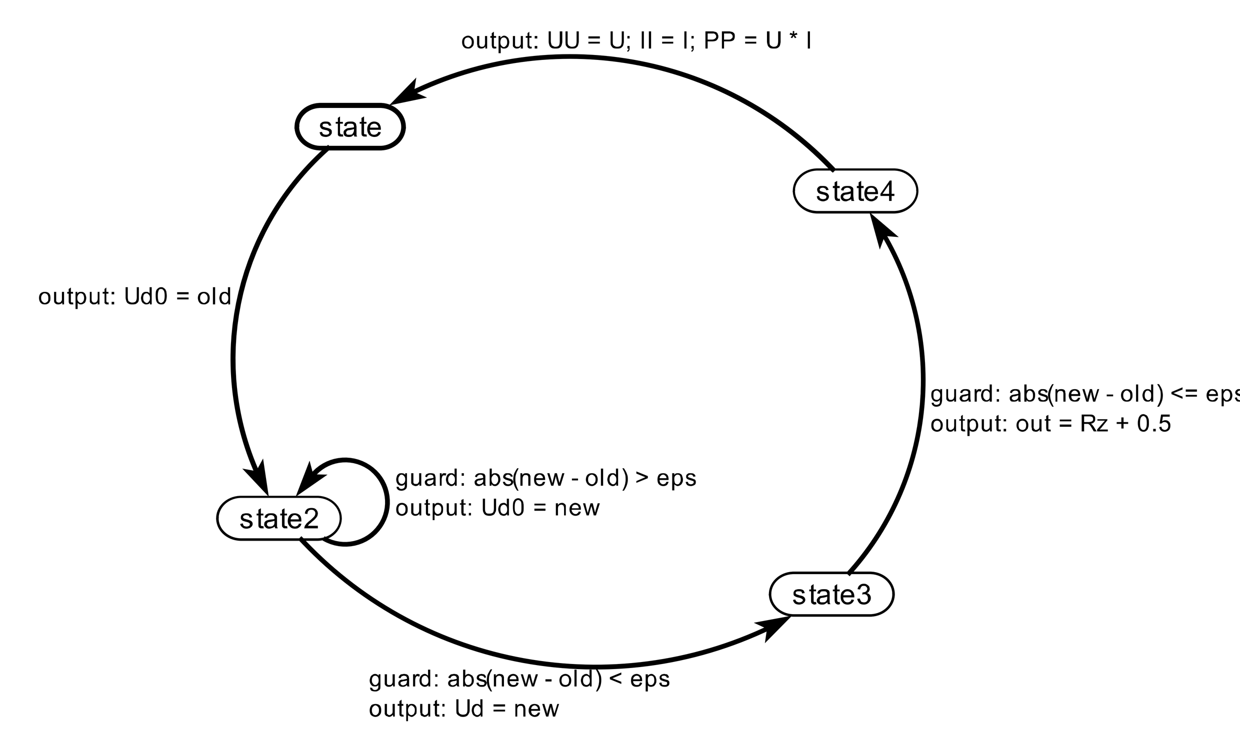
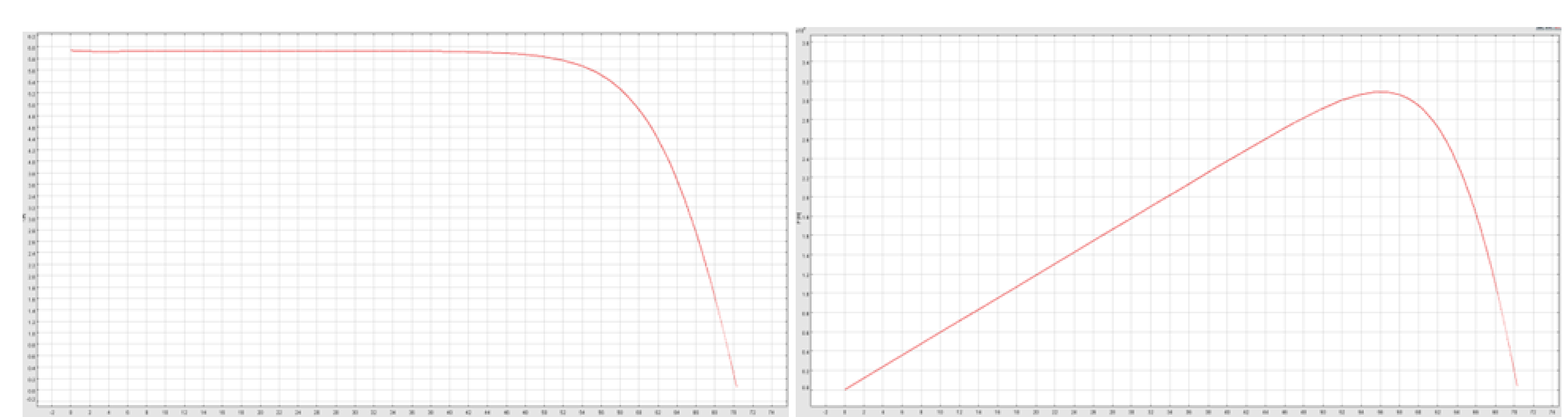


Fig. 4. FSM diagram in the model of PV panel

Then a condition is tested, if the absolute difference between the new and old calculated value of U_d is equal to or less than the required error. Only if the result of this comparison is true, the simulation moves to the "*state*3", in which the value of load resistance R_z is increased by 0.5. Then the output voltage U, output current I and generated power P for given load resistance R_z are calculated in "*state4*" and the simulation returns to FSM initial state, but with the new increased value of load resistance (Fig. 4). Obtained simulations results are presented on Fig. 5, where current-voltage characteristic and power characteristic of modeled PV panel are shown.



a) current-voltage characteristic *b) power characteristic*

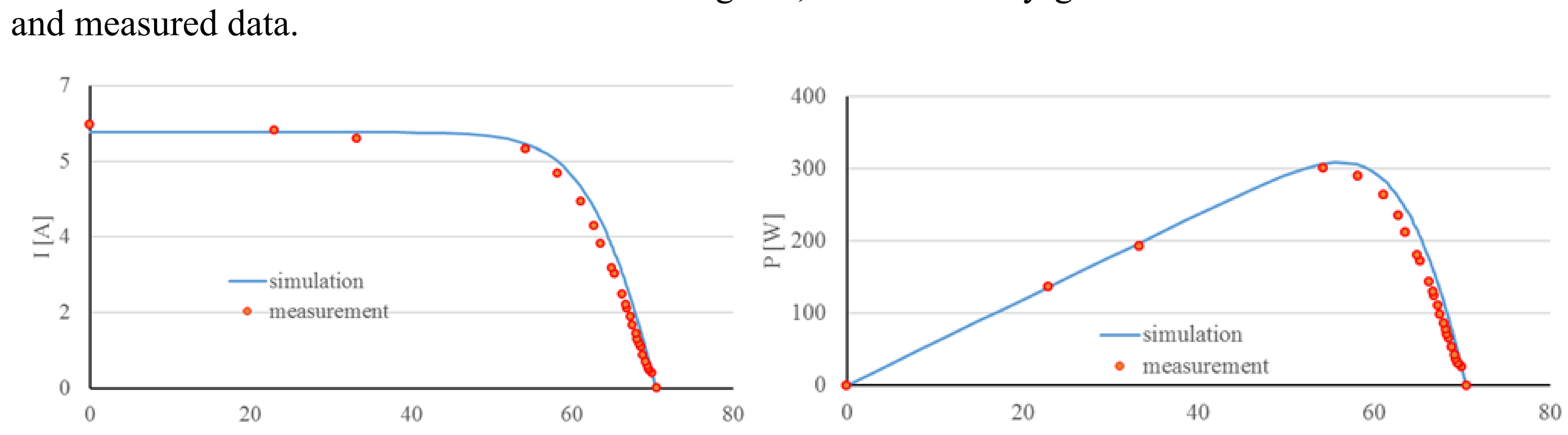
Fig. 5. Simulation results from Ptolemy II

Verification of created simulation model

To verify the results of introduced simulation model, a measurement of the current-voltage characteristic of a small PV installation consisting of two series connected photovoltaic panels were done. One panel consists of two parallel branches of 60 series-connected cells.

All parameters relevant to the measurement were applied to the created FSM model of PV panel (Fig. 3), with respect to the real interconnections of measured PV installation. The main parameters influencing the generated output were a value of ambient temperature (T= 23 °C), a value of solar irradiance (λ = 0.78 kW/m^2) and panel parameters taken from data sheet provided by the manufacturer of used panels. The created simulation model was used to calculate current-voltage characteristic as well as power characteristic of measured PV installation.

Both measured and simulated characteristics were compared. Fig. 6a shows the comparison of the measured and simulated current-voltage characteristics and Fig. 6a shows the same comparison for power characteristics. As it can be seen from both figures, there is a very good correlation between simulated and measured data.



a) current-voltage characteristics *b) power characteristics*

Fig. 6. The comparison of simulated and measured values

Conclusion

The paper describes a nonlinear mathematical model of PV panel consisting of series–parallel connected PV modules. As a calculation method a finite state machine model was used. Advantage of such a model is that one model can be used for the mathematical description of different modes of operation. Presented model is just the introduction of a simulation attitude that will be used for the creation of more complex model of a distribution network with distributed generation.

Acknowledgement

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References

[1] Baherník, M. Höger, M. Braciník, P. Dezelak, K.; "Model of Photovoltaic Power Plant with Constant Resistive Load" 10th International Conference ELEKTRO 2014 [CD-ROM]. ISBN 978-1-4799-3720-2
[2] http://ptolemy.eecs.berkeley.edu/ptolemyII/