

Behavioral Model of Photovoltaic Panel in Simulink®

Karel ZAPLATILEK, Jan LEUCHTER

University of Defence, Kounicova 65, City of Brno 662 10, Czech Republic

karel.zaplatilek@unob.cz, jan.leuchter@unob.cz

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 $P_n = 53$ 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 $T = 45^\circ C$.

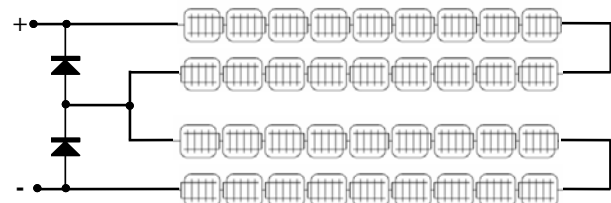


Figure 1. Testing PV panel topology

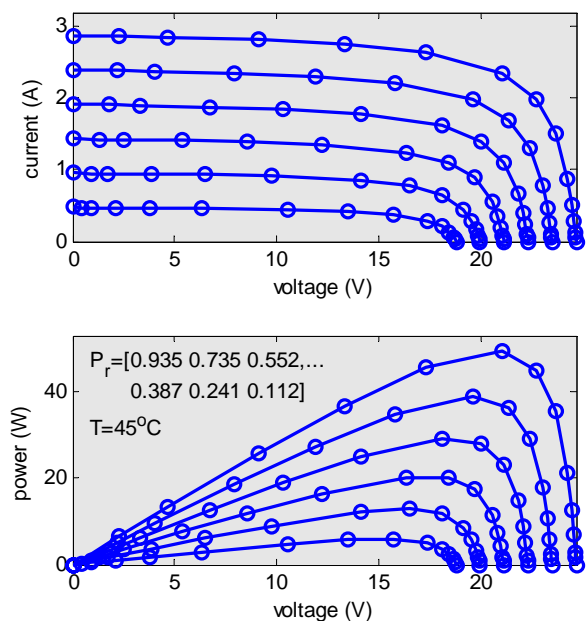


Figure 2. The $i = f(v, P_r)$ measured characteristics for the panel $P_n = 53$ W

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.

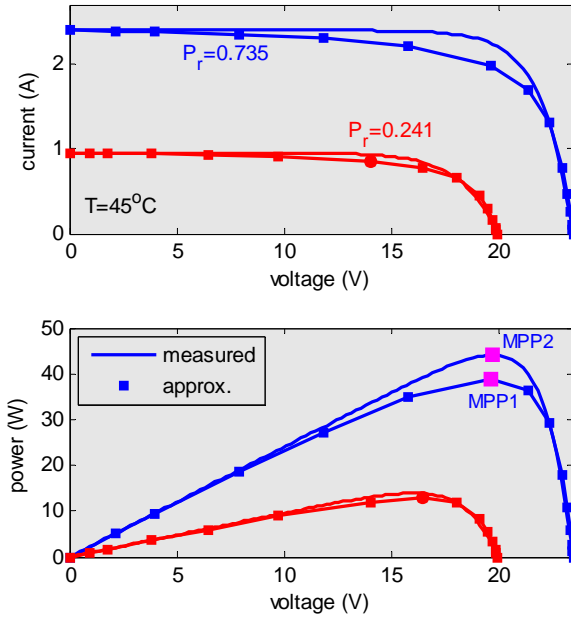


Figure 3. Measured data approximation by the equation (1) application

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:

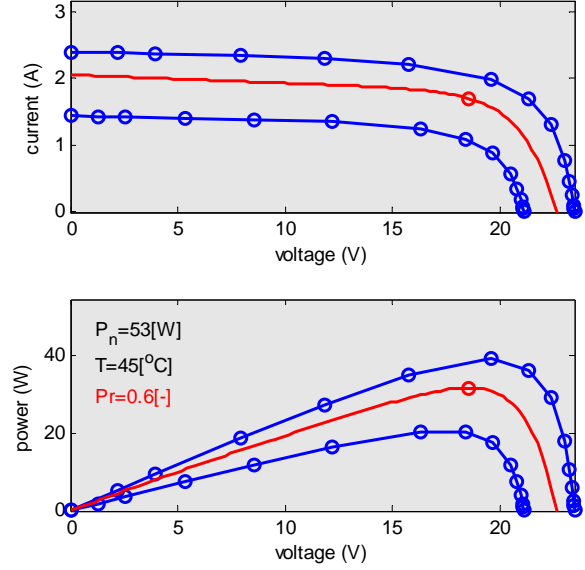
$$K_{corr} = \frac{\Delta P_{mpp}}{P_{mpp}} \cdot \frac{1}{v_{mpp}} [V^{-1}], \quad (2)$$

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 $I_k, I_o, P_{mpp}, V_l, I_l = f(P_r)$ equations. The $[V_l, I_l]$ 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.



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 is used for drawing the $i, p = f(v)$ characteristics.

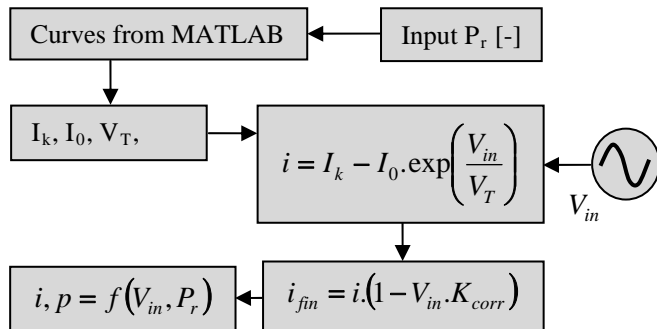


Figure 6. Dynamic model creation process in Simulink

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.

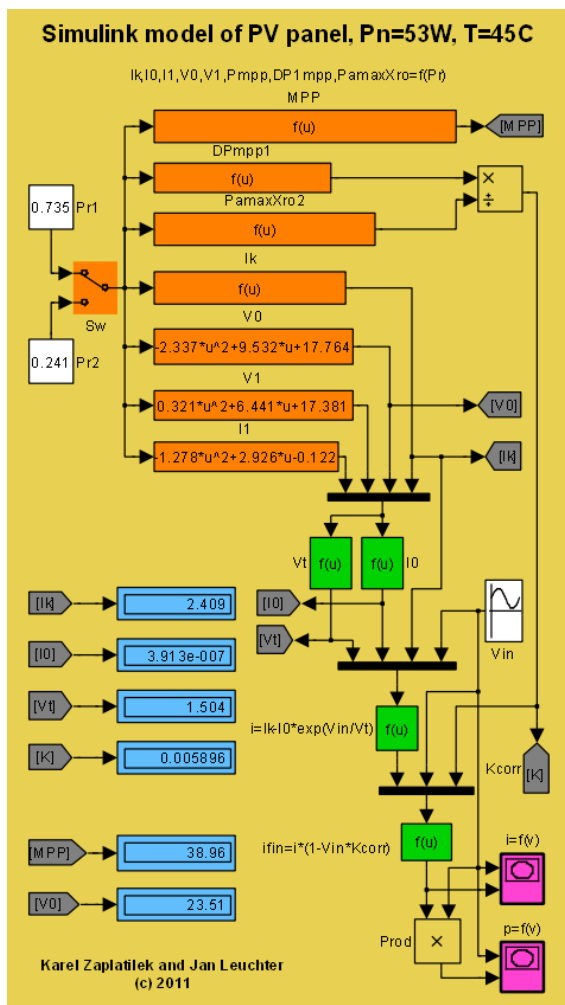


Figure 7. Final PV panel model in Simulink

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

Subsequently, the I_k , I_o , 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.

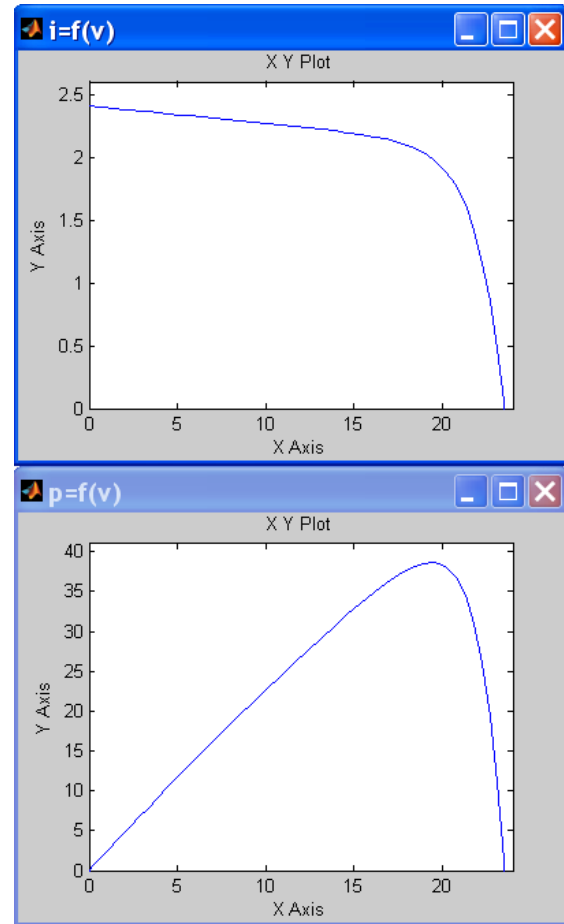


Figure 8. The $i = f(v)$ and $P = f(v)$ characteristics simulation

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.

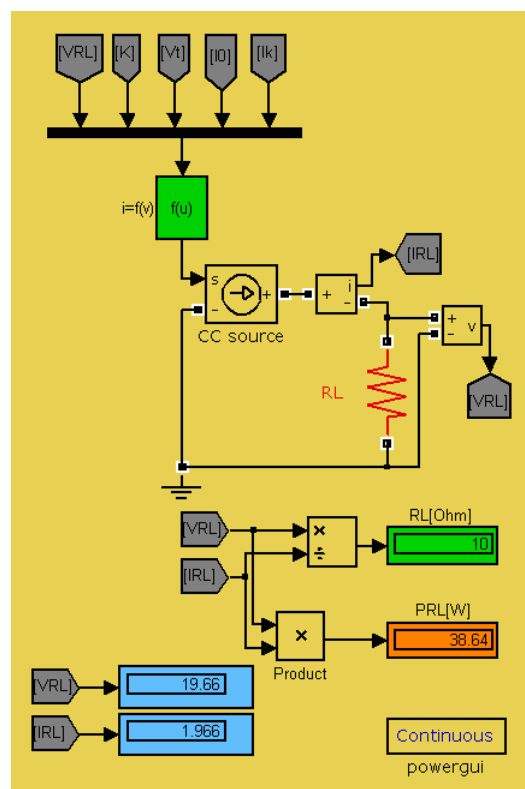


Figure 10. PV panel physical model

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.

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.

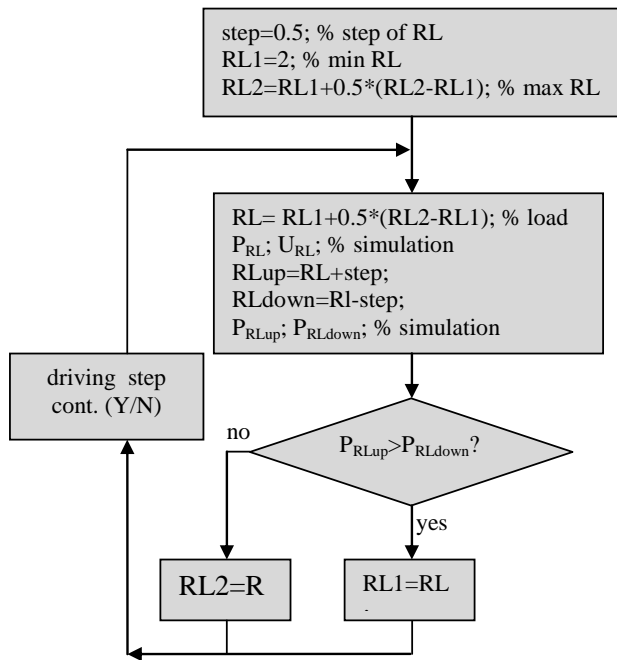


Figure 11. Block diagram of power optimization system

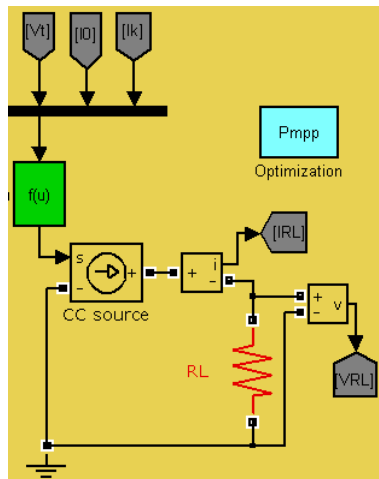


Figure 12. Power optimization callback block

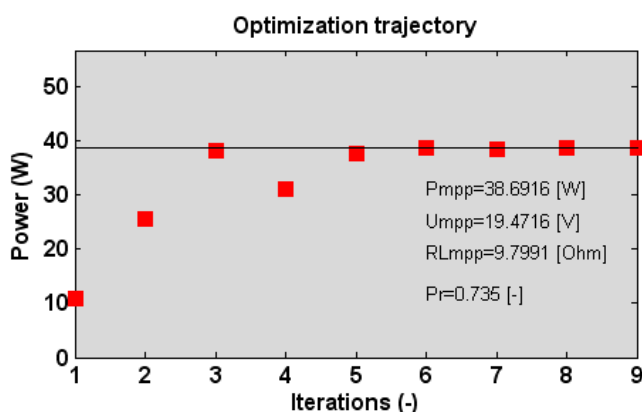


Figure 13. Power optimization result

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.

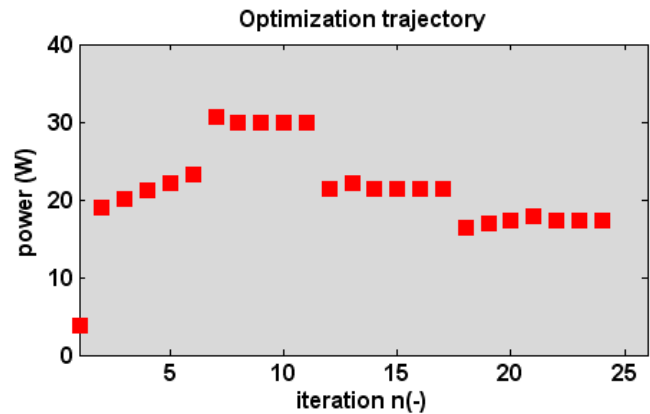


Figure 15. Continuous power optimization

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

The research work is supported by the Grant Agency of the Czech Republic (project No. 102/09/0013) and University of Defence MATLAB Group (*UDeMAG*).

MATLAB® and Simulink® are registered trademarks of The MathWorks, Inc.

REFERENCES

- [1] J. Leuchter, P. Bauer, V. Rerucha, P. Bojda, "dc-dc converters with FPGA control for photovoltaic system," in *Proc. 13th Power Electronics and Motion Control Conference*, Poznan (Poland), 2008, pp. 422-427.
- [2] X. Weidong, W.G. Dunford, A. Capel, "A novel modeling method for photovoltaic cells," in *Proc. 35th Power Electronics Specialists Conference (PESC)*, Aachen (Germany), 2004, pp. 1950-1956.
- [3] J. Leuchter, V. Rerucha, A.F. Zobaa, "Mathematical modeling of photovoltaic systems," in *Proc. 14th Power Electronics and Motion Control Conference (EPE-PEMC)*, Ohrid (Macedonia), 2010, pp. 422-427.
- [4] K. Zaplatilek, J. Leuchter, "Solar panels modelling in MATLAB® environment," *Radionengineering*, 2011, vol. 20, no. 2, pp. 445-450.
- [5] R. Shaffer, *Fundamentals of Power Electronics with MATLAB*. Charles River Media, Boston, 2009.
- [6] J.B. Dabney, T.L. Harman, *Mastering Simulink®*. Pearson Prentice Hall®, 2003.
- [7] S. Yuvarajan, J. Shoeb, "A Fast and Accurate Maximum Power Point Tracker for PV Systems," In *Proc. 23th Applied Power Electronics Conference and Exposition (APEC)*, Austin, 2008, pp. 167-172.
- [8] H. Patel, V. Agarwal, "Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions," *IEEE Transactions on Industrial Electronics*, 2008, vol. 55, no. 4, pp. 1689-1698.
- [9] Ch. Chian-Song, "T-S Fuzzy Maximum Power Point Tracking Control of Solar Power Generation Systems," *IEEE Transactions on Energy Conversion*, 2010, vol. 25, no. 4, pp. 1123-1132.
- [10] S. Mehrnami, S. Farhangi, "A fast maximum power point tracking technique for PV powered systems," in *Proc. 35th Annual Conference of IEEE Industrial Electronics (IECON)*, Porto (Portugal), 2009, pp. 42-46.
- [11] V.P. Benjamin, L. Chong, L. Zhang, D. Abbas, "Modeling and Control of a Bidirectional Converter for a Standalone Photovoltaic Power Plant," in *Proc. EPE Conference 2007*, Aalborg: EPE press.
- [12] R. Diver, C. Andracka, K. Rawlinson, T. Moss, V. Goldberg, G. Thomas, "Status of the Advanced Dish Development System Project," in *Proc. of the ASME International Solar Energy Conference*, Kohala Coast (Hawaii), 2003.
- [13] M. Lotker, *Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the LUZ Experience*. Sandia National Laboratories, Albuquerque, NM, SAND 91-7014.
- [14] F. Chimento, S. Musumeci, A. Raciti, C. Sapuppo, "A Control Algorithm for Power Converter in the Field of Photovoltaic Application," in *Proc. EPE Conference 2007*, Aalborg: EPE press.
- [15] E. de Jong, J.A. Ferreira, P. Bauer, "Design techniques for thermal management in switch mode converters," *IEEE Transactions on Industry Applications*, 2006, vol. 42, no. 6, pp. 1375-1386.
- [16] Y. K. Renani, B. Vahidi, H. A. Abyaneh, "Effects of Photovoltaic and Fuel Cell Hybrid System on Distribution Network Considering the Voltage Limits," *Advances in Electrical and Computer Engineering*, 2010, vol. 10, no. 4, pp. 143-148.
- [17] D. Petreus, D. Moga, A. Rusu, T. Patarau, M. Munteanu, "Photovoltaic System with Smart Tracking of the Optimal Working Point," *Advances in Electrical and Computer Engineering*, 2010, vol. 10, no. 3, pp. 40-47.
- [18] A. Tofighi, A. Kalantar, "Adaptive Passivity-Based Control of PEM Fuel Cell/Battery Hybrid Power Source for Stand-Alone Applications," *Advances in Electrical and Computer Engineering*, 2010, vol. 10, no. 4, pp. 111-120.
- [19] R. A. Messenger, J. Ventre, *Photovoltaic Systems Engineering*. CRC Press, 3rd edition, 2010.
- [20] S. R. Venham, M. A. Green, M. E. Watt, R. Corkish, *Applied Photovoltaics*. Routledge, 2nd edition, 2006.
- [21] J. Nelson, *The Physics of Solar Cells*. Imperial College Press, 1st edition, 2003.
- [22] H. Haberlin, *Photovoltaics: System Design and Practice*. Wiley, 1st edition, 2012.
- [23] J. P. Dunlop, *Photovoltaic Systems*. Amer Technical Pub, 2nd edition, 2009.
- [24] A. Luque, S. Hegedus, *Handbook of Photovoltaic Science and Engineering*. Wiley, 2nd edition, 2011.
- [25] F. Antony, Ch. Durschner, K-H. Remmers, *Photovoltaics for Professionals: Solar Electric Systems Marketing, Design and Installation*. Routledge, 2007.
- [26] A. McEvoy, T. Markvart, L. Castaner, *Practical Handbook of Photovoltaics: Fundamentals and Applications*. Academic Press, 2nd edition, 2011.