

# Development of Parameterized Verilog-AMS Model of Photovoltaic Cells

Elissaveta Gadjeva<sup>1</sup> and Georgi Valkov<sup>2</sup>

**Abstract** – A parameterized Verilog-AMS model of photovoltaic cell, module and panel is developed. The model is available in two variants: one that includes a detailed Spice diode description and the other which is simplified and includes only the diode equations that affect the behavior of the PV elements. Definitions for obtaining the model characteristics from the simulation results are provided. The model is realized in the Dolphin Integration SMASH environment.

**Keywords** – Photovoltaic cells, Parameterized models, Verilog-AMS language.

## I. INTRODUCTION

The design and optimization of photovoltaic systems require development of computer models of PV cells and panels. These models are of significant importance for the simulation of maximum power point tracking (MPPT) control systems and allow the investigation and optimization of the dynamics of PV power systems.

Photovoltaic models of PV cells and modules are developed in [1-3]. Methods for parameter extraction and simulation of photovoltaic modules by taking the manufacturer specified data are developed in [4-6]. A sun-tracking system based on the Verilog HDL and using an FPGA chip as controlling platform is proposed in [7]. Combining all analog and digital blocks of a project, using a behavior HDL like Verilog-AMS and VHDL-AMS [9] allow the entire project to be simulated and verified as a whole. A SoC design of solar irrigation control system based on FPGA is offered in [8].

Parameterized Verilog-AMS macromodel is created in the present paper that can represent a single PV cell, as well as an entire panel consisting of PV cells connected in series and parallel. An additional model using a simplified version of the diode is also described. Definitions for obtaining the model characteristics from the simulation results are provided, according to the pattern file syntax used by SMASH [10].

## II. MODELS OF PV CELL AND PANEL

### A. Model of a single PV cell

The schematic representation of the macromodel for a single PV cell is provided in Fig. 1.  $I_1$  is a DC current source with value  $I_1 = I_{CC} \cdot K_{SH}$ , where  $I_{CC}$  is a function of the solar

irradiation and the shading factor  $K_{SH}$  models the behavior of the cell under reduced light conditions. Its range is [0, 1], where 1 is for unshaded cell.  $R_1$  and  $R_2$  model the shunt and series resistance losses. Their values are  $R_1 = R_{SH}$  and  $R_2 = R_S$ . The diode models the non-linear behavior, its parameters are  $I_S$  and  $N$ , where  $I_S$  is the saturation current and  $N$  is the emission coefficient.

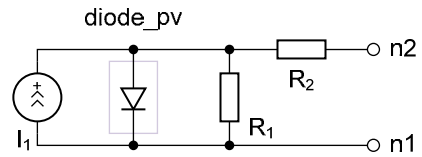


Fig. 1. Parameterized model of a single solar cell.

A generic symbol for the PV cell model is shown in Fig. 2.

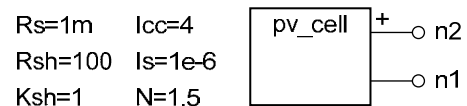


Fig. 2. Generic symbol of PV cell.

### B. Model of PV panel

The model of PV panel uses the same schematic representation as the single PV cell shown in Fig. 1, but with scaled parameters to represent a whole panel. A panel consists of  $N_p$  modules connected in parallel, where each module has  $N_s$  cells connected in series, as shown in Fig. 3.

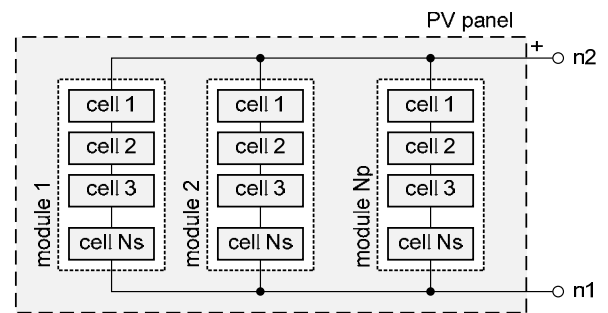


Fig. 3. Structure of PV panel.

In the case when  $N_s=1$  and  $N_p=1$ , the model represents a single PV cell. The values for model parameters are  $I_1 = I_{CC} \cdot K_{SH} \cdot N_p$ ,  $R_1 = R_{SH} \cdot N_p$ ,  $R_2 = R_S \cdot N_s$ ,  $I_S = I_S \cdot N_p$ ,  $N = N \cdot N_s$ .

A generic symbol for the PV panel model is shown in Fig. 4.

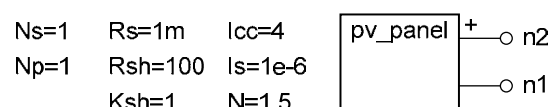


Fig. 4. Generic symbol of PV panel.

<sup>1</sup>Elissaveta Gadjeva is with the Department of Electronics at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: egadjeva@tu-sofia.bg.

<sup>2</sup>Georgi Valkov is with the Department of Electronics at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: gvalkov@abv.bg.

III. VERILOG-AMS IMPLEMENTATION OF PV PANEL

A. Verilog-AMS code of PV panel with full diode description

The Verilog-AMS implementation of the model has the following form:

```

module pv_cell_01_vams(n1, n2);
    inout n1, n2;
    electrical n1, n2, n3;
    parameter real Icc= 4.0;
    parameter real Ksh= 1.0;
    parameter real Rs = 1.0m;
    parameter real Rsh=100.0;
    parameter real Ns = 1.0;
    parameter real Np = 1.0;
    parameter real Is = 1.0u;
    parameter real N = 1.5;
    analog begin
        I(n3, n1) <+ V(n3, n1)*Np/Rsh - Icc*Ksh*Np;
        I(n3, n2) <+ V(n3, n2)*Np/(Ns*Rs);
    end
    diode_pv_sp #(.Is(Is*Np), .N(N*Ns))
        D_pv (.n2(n3), .n1(n1));
endmodule

```

The block has two electrical terminals,  $n_2$  is the positive one and  $n_1$  is the negative. The model parameters are defined. The elements  $I_1$ ,  $R_1$  and  $R_2$  are modeled by their component equations. A diode block is added between nodes  $n_3$  and  $n_1$ , to model the non-linear behavior.

SMASH is a mixed language simulator and allows subcircuits defined using the *Spice* language syntax to be added to Verilog-AMS nets and vice versa. The *diode\_pv\_sp* block wraps a *Spice* diode model inside a subcircuit, using the following *Spice* description:

```

.SUBCKT diode_pv_sp n1 n2 PARAMS: Is=1 N=1
.MODEL diode_pv D (Is=Is N=N)
D1 n2 n1 diode_pv
.ENDS

```

B. Model of PV panel with simplified diode description

For the purpose of simulating PV cells behavior, the diode is only used in forward direction. Additional effects like junction capacitance can also be omitted. Hence it is possible to simplify the model of PV panel with *Spice* diode, by replacing the diode with its equivalent equation. The model is described by the following Verilog-AMS code:

```

module pv_cell_02_vams(n1, n2);
    inout n1, n2;
    electrical n1, n2, n3;
    parameter real Icc = 4.0 from (0: inf);
    parameter real Ksh = 1.0 from [0: 1];
    parameter real Rs = 1.0m from (0: inf);
    parameter real Rsh = 100.0 from (0: inf);
    parameter real Ns = 1.0 from [1: inf];
    parameter real Np = 1.0 from [1: inf];
    parameter real Is = 1.0u from (0: inf);
    parameter real N = 1.5 from (0: inf);
    parameter real Tn = 300.15 from (0: inf);
    parameter real XTI = 3.0 from (0: inf);
    parameter real Eg = 1.11 from (0: inf);
    analog begin
        I(n3, n1) <+ V(n3, n1)*Np/Rsh - Icc*Ksh*Np
        + Np*Is*(exp(V(n3, n1)/(Ns*N*$vt))-1)
        * exp(($temperature/Tn-1)*Eg/(Ns*N*$vt))
        * pow($temperature/Tn, XTI/(Ns*N));
    end
endmodule

```

```

I(n3, n2) <+ V(n3, n2)*Np/(Ns*Rs);
end
endmodule

```

IV. SIMULATED CHARACTERISTICS IN DOLPHIN INTEGRATION SMASH

The characteristics for the Verilog-AMS model of PV panel with full diode description are obtained for a single cell using DC sweep as the primary simulation analysis. To determine the dependence on  $R_s$ ,  $R_{SH}$ ,  $K_{SH}$  and temperature, the following parametric sweeps are run together with the primary analysis:  $R_s$ : value list: 0.1m, 1m, 10m, 100m;  $R_{SH}$ : value list: 1, 10, 100;  $K_{SH}$ : linear from 0.25 to 1, with a step size of 0.25 and  $TEMPER$ : linear from 0 to 75, with a step size of 25. The remaining model parameters are given in Fig. 4.

The current and power characteristics are obtained using the waveforms  $I(V_1)$  and  $IN(V_1.POWER)$ . The following characteristics are also obtained from the simulation results: current and voltage at the maximum power point  $I_{PP}$  and  $V_{PP}$ , fill factor  $FF$ , maximum power  $P_{MAX}$ , short circuit current  $I_{SC}$ , and open circuit voltage  $V_{OC}$ . The parameter  $FF$  is defined as follows:

$$FF = \frac{P_{MAX}}{P_T}, \quad (1)$$

where:  $P_{MAX} = \max(P), \quad (2)$

$$P_T = I_{SC} V_{OC}. \quad (3)$$

The definitions for obtaining  $P_{MAX}$ ,  $I_{SC}$ ,  $V_{OC}$ ,  $P_T$ ,  $FF$ ,  $V_{PP}$ , and  $I_{PP}$  from the simulation results are created using the *MEASURE* command according to the pattern file syntax used by SMASH:

```

.MEASURE ANALYSIS=DC NAME=Pmax
+ WAVEFORM=IN(V1.POWER) EXTRACT=MAX
.MEASURE ANALYSIS=DC NAME=Isc
+ WAVEFORM=I(V1) EXTRACT=MAX
.MEASURE ANALYSIS=DC NAME=Voc
+ WAVEFORM=I(V1) EXTRACT=X ATY=0
+ CROSS=DOWN OCCUR=1
.MEASURE ANALYSIS=DC NAME=PT VALUE={Isc*Voc}
.MEASURE ANALYSIS=DC NAME=FF VALUE={Pmax/PT}
.MEASURE ANALYSIS=DC NAME=Vpp
+ WAVEFORM=IN(V1.POWER) EXTRACT=ATMAX ATY=0
.MEASURE ANALYSIS=DC NAME=Ipp
+ WAVEFORM=I(V1) EXTRACT=Y ATX=Vpp

```

The current and power characteristics as a function of  $R_s$  are shown in Fig. 5.

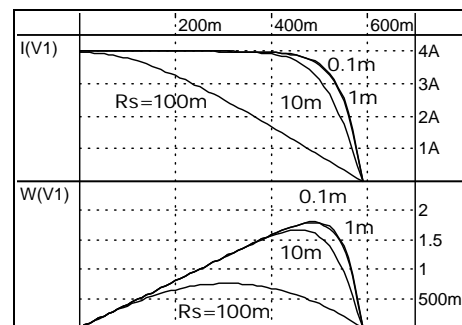


Fig. 5. Current and power characteristics as a function of  $R_s$ :  $I(V_1, R_s)$  and  $P(V_1, R_s)$ .

High values for the series resistance tend to cause a significant drop in the output power of the PV elements as well as reduction of  $I_{PP}$ ,  $V_{PP}$  and  $FF$  (Fig. 6).

The current and power characteristics as a function of  $R_{SH}$  are shown in Fig. 7. High values for the shunt resistance have no impact on the performance, while low values act like an additional consumer, reducing the power at the output of the PV elements and also reducing  $I_{PP}$ ,  $V_{PP}$  and  $FF$  (Fig. 8). The shading factor  $K_{SH}$  indicates what part of the PV cell or panel is not shaded. The output current is proportional to the solar irradiation and hence proportional to  $K_{SH}$ . Lower values for  $K_{SH}$  result in a lower output power (Fig. 9), and also cause a reduction in  $I_{PP}$ ,  $V_{PP}$  and  $FF$ , as shown in Fig. 10.

The temperature dependences of the output current and power characteristics as a function of  $R_S$  are shown in Fig. 11. At lower temperatures  $V_{OC}$  and  $V_{PP}$  are higher. As a result the I-V characteristic is shifted to the right; the output power at the maximum power point and  $FF$  are also higher. There is also a small increase in  $I_{PP}$  (Fig. 12).

The model of simplified PV panel is compared to the PV panel model with full diode description. The temperature dependence of the I-V characteristic is shown in Fig. 13.

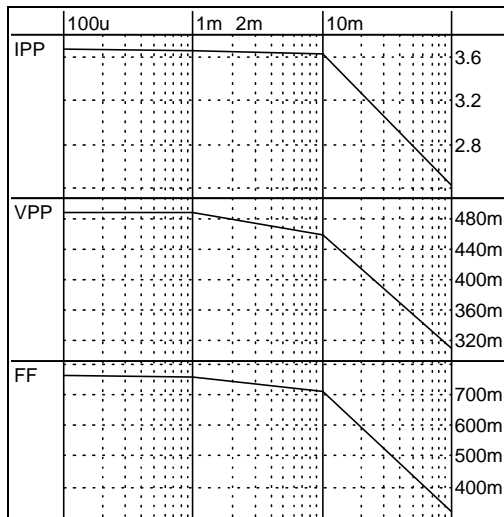


Fig. 6.  $I_{PP}$ ,  $V_{PP}$  and  $FF$  characteristics as a function of  $R_S$ :  $I_{PP}(R_S)$ ;  $V_{PP}(R_S)$  and  $FF(R_S)$ .

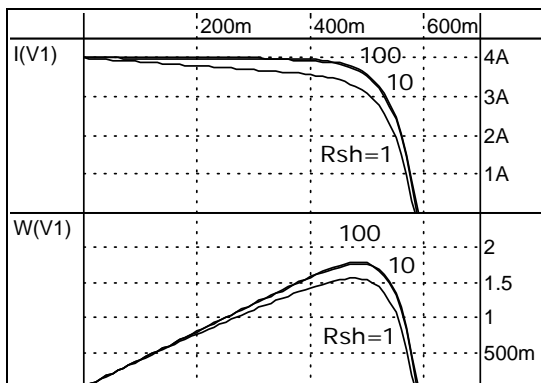


Fig. 7. Current and power characteristics as a function of  $R_{SH}$ :  $I(V_1, R_{SH})$  and  $P(V_1, R_{SH})$ .

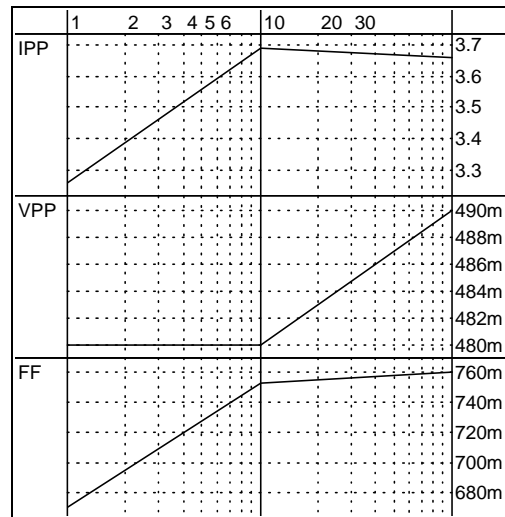


Fig. 8.  $I_{PP}$ ,  $V_{PP}$  and  $FF$  characteristics as a function of  $R_{SH}$ :  $I_{PP}(R_{SH})$ ;  $V_{PP}(R_{SH})$  and  $FF(R_{SH})$ .

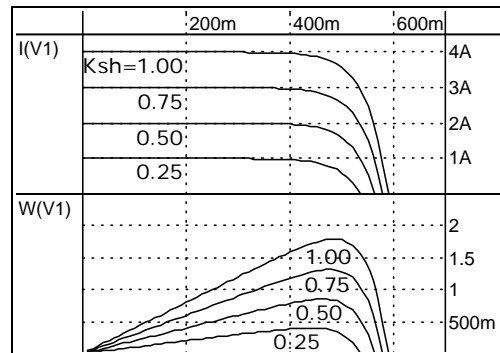


Fig. 9. Current and power characteristics as a function of  $K_{SH}$ :  $I(V_1, K_{SH})$  and  $P(V_1, K_{SH})$ .

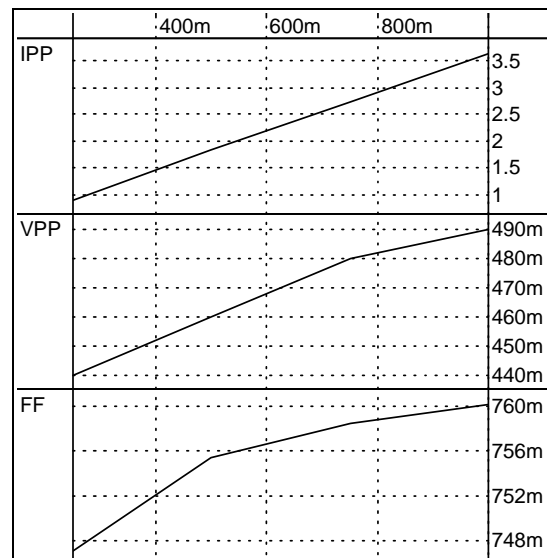


Fig. 10.  $I_{PP}$ ,  $V_{PP}$  and  $FF$  characteristics as a function of  $K_{SH}$ :  $I_{PP}(K_{SH})$ ;  $V_{PP}(K_{SH})$  and  $FF(K_{SH})$ .

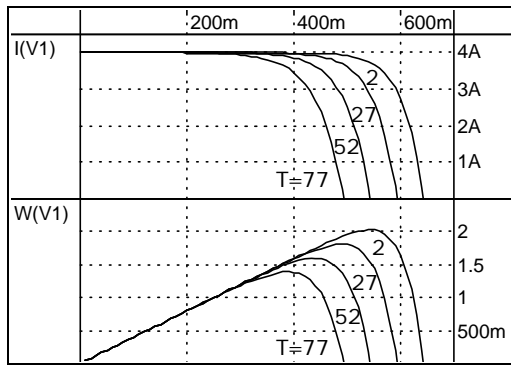


Fig. 11. Current and power characteristics as a function of the temperature:  $I(V_1, T)$  and  $P(V_1, T)$ .

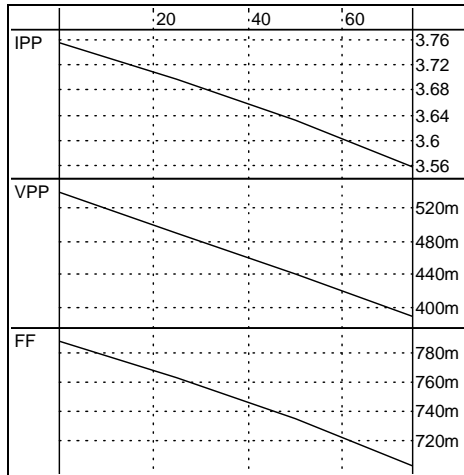


Fig. 12.  $I_{PP}$ ,  $V_{PP}$  and  $FF$  characteristics as a function of the temperature:  $I_{PP}(T)$ ;  $V_{PP}(T)$  and  $FF(T)$ .

The current characteristics match for all of the simulated temperatures. The relative difference is smaller than  $2 \times 10^{-6} \%$ , hence it is advisable to use the simplified model in order to speed the simulation of large circuits, as the accuracy is not sacrificed.

### V. CONCLUSIONS

A behavioral parameterized Verilog-AMS macromodel has been developed for PV cell and PV panel consisting of cells connected in series and in parallel. The model of PV panel can also represent a single cell. The detailed model relies on a *Spice* diode model to describe the non-linear behavior of the PV cell. An alternative simplified model is also provided. It includes only the diode equations that are important for the modeling of the PV behavior. It is a pure Verilog-AMS implementation, and does not depend on mixed language simulators. Both models are simulated in the Dolphin Integration SMASH environment. The basic PV characteristics are obtained from the simulation results.

### ACKNOWLEDGEMENT

The investigations are supported by the project №122PD0026-03.

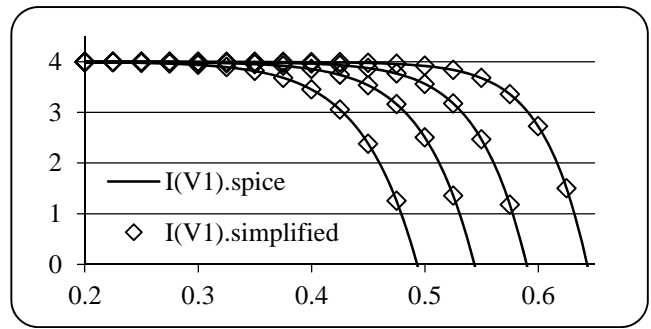


Fig. 13. Comparison between the model with *Spice* diode and the simplified model. Current and power characteristics as a function of the temperature:  $I(V_1, T)$  and  $P(V_1, T)$ .

### REFERENCES

- [1] H-L., Tsai, Ci-Siang Tu, and Yi-Jie Su. "Development of generalized photovoltaic model using MATLAB/SIMULINK", Proceedings of the World Congress on Engineering and Computer Science 2008, WCECS 2008, October 22 - 24, San Francisco, USA, 2008.
- [2] I.H., Altas, A.M., Sharaf. "A photovoltaic array simulation model for Matlab-Simulink GUI environment", International Conference on Clean Electrical Power., ICCEP '07. 21-23 May 2007, pp. 341 – 345, Capri, 2007.
- [3] Hernanz, R., C. Martín, J.J. Belver, L. Lesaka, Z. Guerrero, E. Puelles Pérez."Modelling of photovoltaic module", International Conference on Renewable Energies and Power Quality, (ICREPO'10) Granada (Spain), 23th to 25th March, 2010.
- [4] D. Sera, R. Teodorescu, P. Rodriguez. "PV panel model based on datasheet values", IEEE International Symposium on Industrial Electronics, ISIE 2007, June 4-7 2007, Vigo, Spain, ISBN: 978-1-4244-0754-5, pp. 2392-2396, 2007.
- [5] G. Farivar and B. Asaei. "Photovoltaic module single diode model parameters extraction based on manufacturer datasheet parameters", IEEE International Conference on Power and Energy, PECon 2010 Nov. 29-Dec. 1 2010, Selangor, Malaysia, ISBN: 978-1-4244-8947-3, pp. 929-934, 2010.
- [6] N.N.B. Ulapane, C.H. Dhanapala, S.M. Wickramasinghe, S.G. Abeyratne, N. Rathnayake and P.J. Binduhewa. "Extraction of parameters for simulating photovoltaic panels", 2011 IEEE 6th International Conference on Industrial and Information Systems (ICIIS), 16-19 Aug. 2011, Peradeniya, Sri Lanka, ISBN: 978-1-4577-0032-3, pp. 539-544, 2011.
- [7] Cheng Sen, Zhao Ping, He Hongkun, Ji Qianqian and Wei Xu. "An improved design of photo-voltaic solar tracking system based on FPGA", AICT'10, International Conference on Artificial Intelligence and Computational Intelligence, 23-24 October 2010, Sanya, China, ISBN: 978-1-4244-8432-4, pp. 267-271. 2010.
- [8] Ze Cheng, Dan Zhong, Baolin Li and Yanli Liu. "The SoC design and realization of small scale solar irrigation control system based on FPGA", 2011 International Conference on Electric Information and Control Engineering (ICEICE), Apr. 15-17, 2011, Wuhan, China, ISBN: 978-1-4244-8036-4, pp. 887-890, 2011.
- [9] F. Pêcheux, C. Lallement, A. Vachoux, "VHDL-AMS and Verilog-AMS as Alternative Hardware Description Languages for Efficient Modeling of Multi-Discipline Systems", Paper #1446, IEEE, ISSN 0278-0070, 2005.
- [10] Dolphin Integration SMASH overview, [http://www.dolphin.fr/medal/smash/smash\\_overview.php](http://www.dolphin.fr/medal/smash/smash_overview.php)