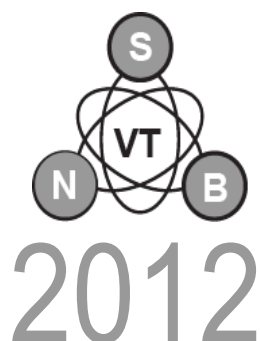


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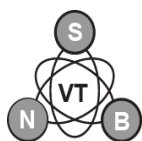
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VOLUME 1

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Development of Parameterized Verilog-AMS Model of Photovoltaic Cells

Elissaveta Gadjeva¹ and Georgi Valkov²

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.

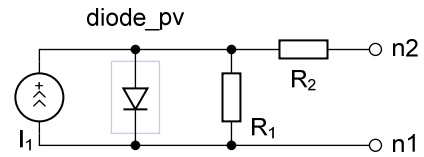


Fig. 1. Parameterized model of a single solar cell.

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

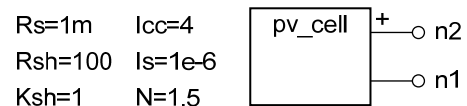


Fig. 2. Generic symbol of PV cell.

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.

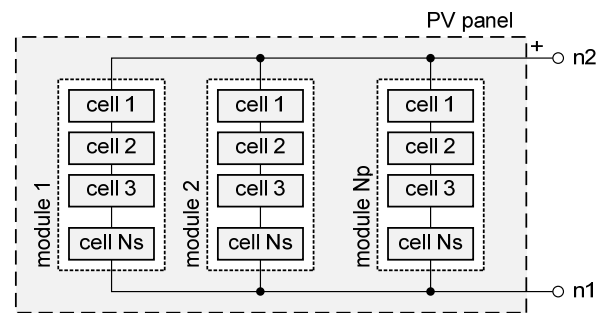


Fig. 3. Structure of PV panel.

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.

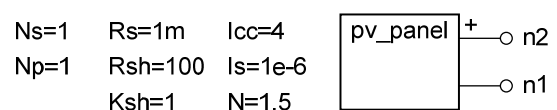


Fig. 4. Generic symbol of PV panel.

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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));

```

```

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.

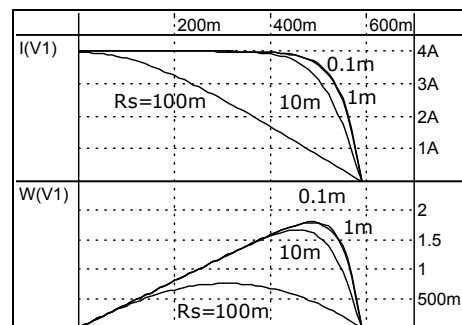


Fig. 5. Current and power characteristics as a function of R_S : $I(V_1, R_S)$ and $P(V_1, R_S)$.

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.

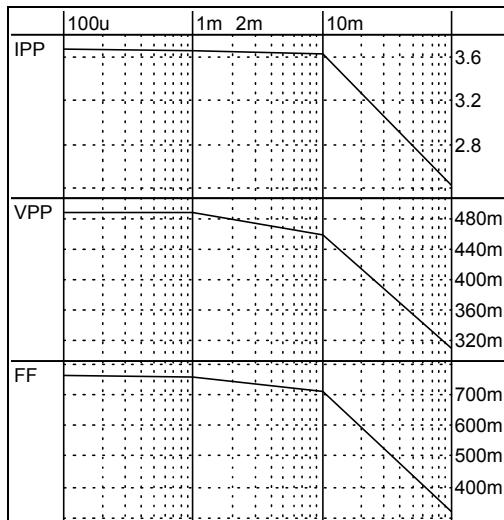


Fig. 6. I_{PP} , V_{PP} and FF characteristics as a function of R_S : $I_{PP}(R_S)$; $V_{PP}(R_S)$ and $FF(R_S)$.

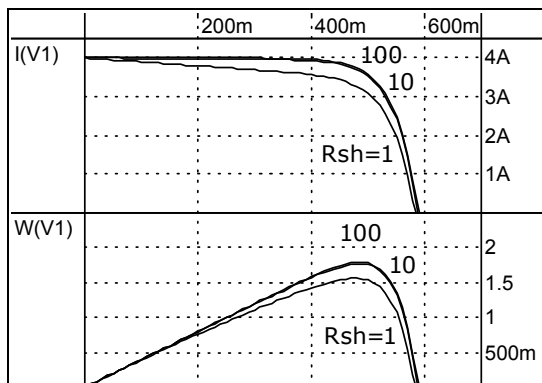


Fig. 7. Current and power characteristics as a function of R_{SH} : $I(V_1, R_{SH})$ and $P(V_1, R_{SH})$.

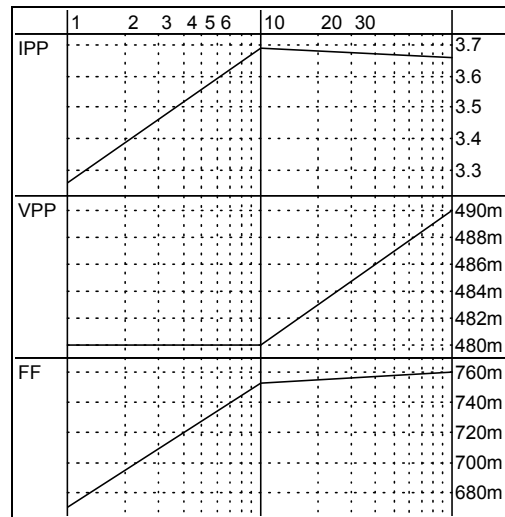


Fig. 8. I_{PP} , V_{PP} and FF characteristics as a function of R_{SH} : $I_{PP}(R_{SH})$; $V_{PP}(R_{SH})$ and $FF(R_{SH})$.

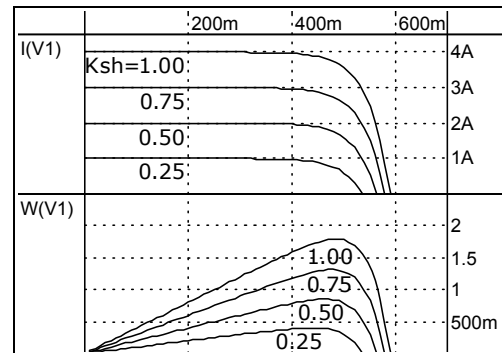


Fig. 9. Current and power characteristics as a function of K_{SH} : $I(V_1, K_{SH})$ and $P(V_1, K_{SH})$.

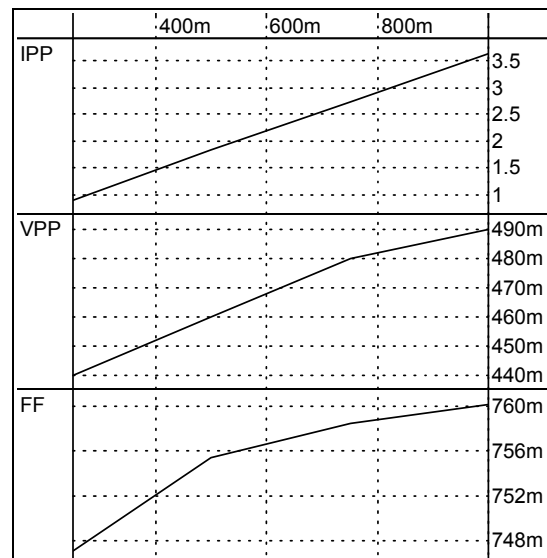


Fig. 10. I_{PP} , V_{PP} and FF characteristics as a function of K_{SH} : $I_{PP}(K_{SH})$; $V_{PP}(K_{SH})$ and $FF(K_{SH})$.

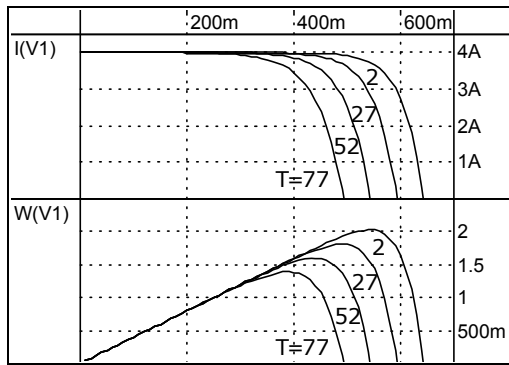


Fig. 11. Current and power characteristics as a function of the temperature: $I(V_1, T)$ and $P(V_1, T)$.

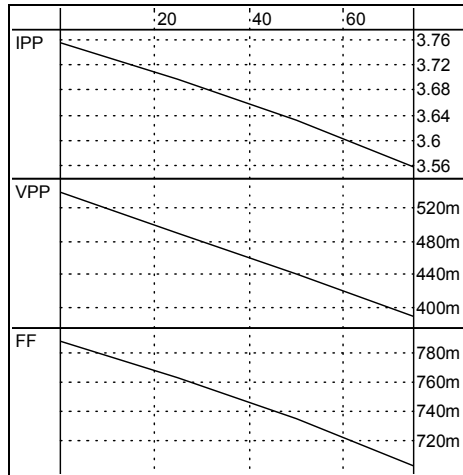


Fig. 12. I_{PP} , V_{PP} and FF characteristics as a function of the temperature: $I_{PP}(T)$; $V_{PP}(T)$ and $FF(T)$.

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.

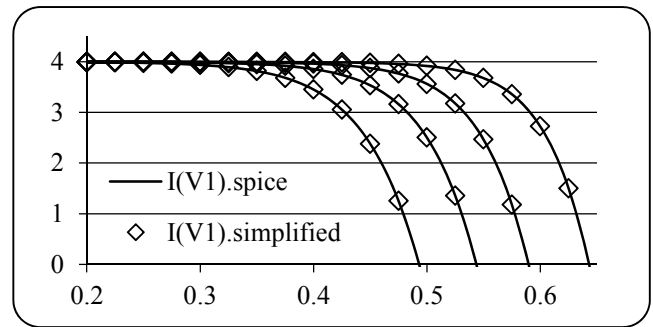


Fig. 13. Comparison between the model with *Spice* diode and the simplified model. Current and power characteristics as a function of the temperature: $I(V_1, T)$ and $P(V_1, T)$.

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