HARDWARE MODELING OF PHOTOVOLTAIC PANELS

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Abstract – A hardware model of photovoltaic modules is proposed in this paper. The model consists in the hardware implementation of a power circuit derived from the basic circuit model of a photovoltaic cell. The current source is implemented by a current-controlled chopper, fed by a dc voltage source. The nonlinear *I-V* characteristic is obtained by a series array of diodes. The chopper current, smoothed by an inductive filter, represents the solar irradiance, whereas variable resistors are introduced to account for the temperature variations. The proposed model is useful for testing both the hardware and the control strategies of the link converters employed to connect the photovoltaic panels to the grid or to a storage unit, reducing the size and shooting down the cost of the whole system prototype. In this way, the laboratory tests are unaffected by the external weather conditions, and arbitrary transients or steady-state conditions can be reproduced, corresponding to the different environmental cases of interest. The current regulator of the chopper is tuned by a transfer function analysis and the behavior of the hardware model is verified by numerical simulations.

1. INTRODUCTION

The energy from photovoltaic (PV) panels seems to become one of the most important renewable energy resources in the near future, since it is clean, pollution free, and inexhaustible. Nowadays, despite of the known advantages, the installation cost is still high and the PV energy is not competitive yet with respect to the traditional fossil-based energy resources.

Since PV modules still have relatively low conversion efficiency, minimizing the losses in the power electronic converters, and maximizing the electric power extracted from the PV source can substantially reduce the whole system cost.

Due to the rapid growth in semiconductors and power electronic techniques, the solar energy is of increasing interest in electrical power applications, and a large research activity has been carried out in this field over the last years. In particular, improved algorithms are studied and proposed to maximize efficiency of the PV modules (maximum power point tracking, MPPT) and optimized switching converter configurations are considered to improve the electrical conversion efficiency for connecting the PV panels to the grid or to a storage device [1]-[3].

Then, a numerical model of the PV modules is necessary for research and developments. Usually, circuit models are preferred for the numerical implementation of the whole PV conversion system by circuit-oriented simulation packages.

The prototype realization of the PV conversion system is a crucial point, to practically verify the control strategies and to test the hardware set-up. The drawbacks of a prototype realization are mainly the high PV modules' cost and the wide external area required to arrange them. For these reasons, reduced scale prototypes are often realized.

In this paper an alternative solution is proposed, introducing a hardware model to represent the real electric behavior of the PV modules. In this way, an economic full-scale prototype can be realized indoor, and arbitrary transients or steady-state environmental parameters can be reproduced, despite of the external weather conditions. If the proposed hardware model is applied to a single module, a PV array can be built by a series/parallel connection of hardware models. In this way, the effect of shadows, different solar irradiation or temperature variation for each PV module of the array can be represented. Otherwise, a single hardware model can be fitted to represent the whole PV array, even more reducing the cost up to few percent with respect to commercial PV modules.

2. CIRCUIT MODEL OF PV MODULES

An equivalent electric circuit representing the physics of a PV cell is adopted to model the behavior of PV panels. Essentially two kinds of models, i.e., "single" and "double exponential", can be found in literature for simulating the *I-V* behavior of a photovoltaic cell [4]-[8]. The single exponential model is directly derived by a one-dimensional study of the basic equations for a single solar cell with a single p-n junction [4]. Both models represent the static *I-V* characteristic for assigned irradiance level and cell temperature.

PV cell has in general a sufficiently fast response time with the irradiance variation so a dynamical cell behavior with the above variable may be neglected. Nevertheless a dynamical cell behavior with the temperature based on thermodynamic considerations is encouraged.

The model considered in this paper is an equivalent circuit based on the "single exponential" approach, as represented in (1) and corresponding to the circuit of Fig. 1.

$$i = i_{ph} - i_o \left[exp\left(\frac{v + r_s\, i}{A\, V_t} \right) - 1 \right] - \frac{v + r_s\, i}{r_p} \qquad (1)$$

In spite of offering a closer representation of the solar cell, the "double exponential" model is not considered because the recombination that is incurred by the second diode dominates at low voltage and low irradiance, which are operating conditions out of the range of interest when the PV panels are used as a power source [7].

Since a PV module consists in a series connection of N_s solar cells, a circuit model representing the behavior of the whole PV module can be built by connecting in series N_s of the basic circuits described by (1). Considering identical PV cells leads to [8]

$$i = i_{ph} - i_o \left[exp\left(\frac{v + R_s\, i}{n\, V_t} \right) - 1 \right] - \frac{v + R_s\, i}{R_p}, \qquad (2)$$

where the following equivalent parameter are introduced

$$R_s = N_s\, r_s\,,\;\; R_p = N_s\, r_p\,,\; n = N_s\, A\,. \qquad (3)$$

3. MODEL PARAMETER EVALUATION

The analytical form expressed by (2) is not user-friendly, being nonlinear and implicit. A large number of more or less complex methods can be found in literature to extract from data measurements or data sheets the unknown parameters of the models. These methods mainly consist in

- numerical algorithms, requiring powerful mathematical tools and iterative routines to solve the implicit nonlinear equation associated with the photovoltaic device,
- analytical methods, introducing a series of simplifications and approximations and leading to simpler solutions with an acceptable accuracy.

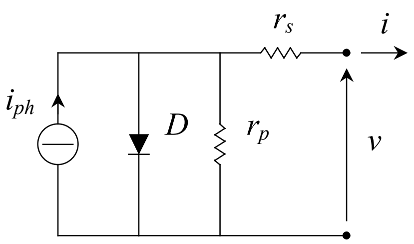


Fig. 1. Basic circuit model of a single PV cell

In this paper the circuit unknown parameters I_o, I_{ph}, R_s, R_{sh}, and n are determined on the basis of the datasheet *I-V* characteristics of the PV panel. In particular, the considered working points, are

$$\begin{cases} ① \rightarrow \text{short-circuit: current, } I_{sc} \\ ② \rightarrow \text{open circuit: voltage, } V_{oc} \\ ③ \rightarrow \text{maximum power point: } V_{MPP},\, I_{MPP} \end{cases} \qquad (4)$$

$$④ \rightarrow \text{maximum power condition: } \left.\frac{\partial p}{\partial v}\right|_{v=V_{MPP}} = 0$$

$$\rightarrow \frac{\partial p}{\partial v} = i + v\frac{\partial i}{\partial v} \;\; \Rightarrow \;\; \left(\frac{\partial i}{\partial v} = -\frac{i}{v} \right)_{v=V_{MPP}}.$$

These relevant points are emphasized in Fig. 2. The condition of current slope close to zero at short-circuit point in the *I-V* diagram can be useful also.

By introducing in (2) the conditions (4) leads to:

$$\begin{cases} I_{sc} = I_{ph} - I_o \left[exp\left(\frac{R_s I_{sc}}{n\, V_t} \right) - 1 \right] - \frac{R_s\; I_{sc}}{R_p} \\ 0 = I_{ph} - I_o \left[exp\left(\frac{V_{oc}}{n\, V_t} \right) - 1 \right] - \frac{V_{oc}}{R_p} \\ I_{MPP} = I_{ph} - I_o \left[exp\left(\frac{V_{MPP} + R_s I_{MPP}}{n\, V_t} \right) - 1 \right] - \frac{V_{MPP} + R_s I_{MPP}}{R_p} \end{cases} \qquad (5)$$

Assuming n and R_s as parameter, (5) can be solved as a linear equation system in the unknown variable I_o, $1/R_p$, I_{ph}, and rewritten as:

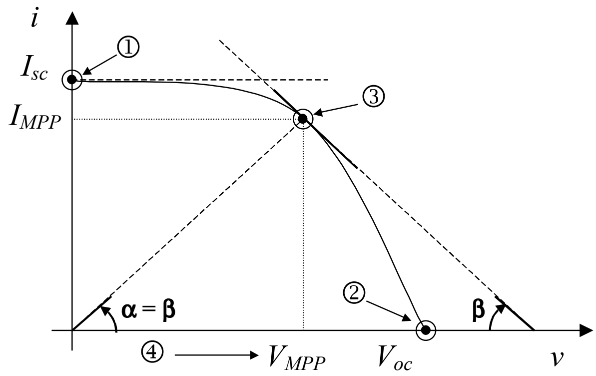


Fig. 2. Relevant points on the *I-V* characteristic of the PV panel

$$\begin{cases} (A_1 - 1)\, I_o + R_s I_{sc} \dfrac{1}{R_p} - I_{ph} = -I_{sc} \\ (A_2 - 1)\, I_o + V_{oc} \dfrac{1}{R_p} - I_{ph} = 0 \\ (A_3 - 1)\, I_o + (V_{MPP} + R_s I_{MPP}) \dfrac{1}{R_p} - I_{ph} = -I_{MPP} \end{cases} \quad (6)$$

where

$$\begin{cases} A_1(n, R_s) = e^{\frac{R_s I_{sc}}{n V_t}} \\ A_2(n) = e^{\frac{V_{oc}}{n V_t}} \\ A_3(n, R_s) = e^{\frac{V_{MPP} + R_s I_{MPP}}{n V_t}} \; . \end{cases} \quad (7)$$

The solution of the system yields

$$\begin{cases} \dfrac{1}{R_p} = \dfrac{(A_1 - A_2)\, I_{MPP} + (A_3 - A_2)\, I_{sc}}{(A_1 - A_2)(V_{MPP} + R_s I_{MPP}) + (A_3 - A_1) V_{oc} + (A_2 - A_3) R_s I_{sc}} \\ I_o = \dfrac{(V_{oc} - R_s I_{sc})\; 1/R_p - I_{sc}}{(A_1 - A_2)} \\ I_{ph} = (A_2 - 1)\, I_o + V_{oc}\; 1/R_p \; . \end{cases} \quad (8)$$

The fourth condition of (4) can be rewritten as

$$-\frac{\dfrac{I_o}{n V_t} exp\left(\dfrac{V_{MPP} + R_s I_{MPP}}{n V_t}\right) + \dfrac{1}{R_p}}{1 + \dfrac{I_o\; R_s}{n V_t} exp\left(\dfrac{V_{MPP} + R_s I_{MPP}}{n V_t}\right) + \dfrac{R_s}{R_p}} = -\frac{I_{MPP}}{V_{MPP}} \quad (9)$$

By introducing (8) in (9) a solving equation is obtained in the form:

$$f(n, R_s) = 0 \; . \quad (10)$$

Equation (9) represents the values of n and R_s satisfying all the four conditions expressed in (4).

The locus $f\,(n, R_s) = 0$ can be drown as a contour line of the function $f\,(n, R_s)$, and an additional condition can be assigned to determine a unique solution. In example, n can be determined by (3) evaluating the parameter A and the number of cells in series N_s. Otherwise, the condition of current slope close to zero at the short-circuit point in the *I-V* diagram can be assigned.

4. PROPOSED HARDWARE MODEL

The proposed hardware model for the PV module is based on the hardware implementation of (2), introducing some approximation to obtain a practical feasibility.

As shown by (2), the single exponential characteristic of the whole PV module could be represented by a series connection of N_s diodes. The goal is to obtain a circuit in which the irradiance is represented by the current i_{ph} of the current generator, and the temperature is represented by the number of the series diodes and the values of the circuit resistances. For this purpose, an additional resistor R_D is introduced in series with the diodes, leading to the circuit depicted in Fig. 2.

The number N_D of the series-connected diodes depends on the chosen diodes type, with reference to their *I-V* characteristic. Usually, a reduced diodes number is sufficient to represent the exponential characteristic shown in (2), leading to $N_D < N_s$.

A current-controlled buck chopper is employed to implement the current generator, introducing an output filter to suppress the high frequency components introduced by the PWM switching operation. The dc voltage V_{dc} supplying the chopper is obtained by a diode rectifier coupled to a step-down transformer, also useful to ensure the electrical insulation from the utility grid.

4.1 Current controller

The buck chopper is controlled to keep the output current i_{ph} close to its reference value i_{ph}^*, representing the solar irradiance. The block diagram of the proposed control scheme is represented in Fig. 3 in terms of *Laplace* transform. In this case, only the inductor L is considered as filter to smooth the current ripple.

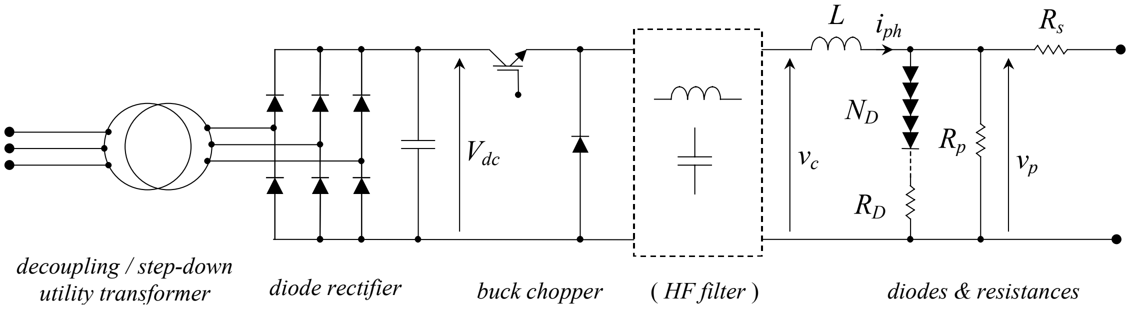


Fig. 2. Proposed hardware model for PV modules

The control scheme shown in Fig. 3 includes the compensation of the load changes, affecting the system in terms of voltage perturbations. For this reason, the voltage V_p is measured and introduced as feed-forward signal. On the basis on an average analysis, assuming an ideal chopper able to generate an output average voltage V_c identical to the reference voltage V_c^* given by the current controller, the output current I_{ph} can be expressed as

$$I_{ph} = \frac{R(s)}{R(s) + s\,L}\, I_{ph}{}^{*}. \tag{10}$$

A transfer function of the first order is obtained by choosing as regulator $R(s)$ a simple proportional gain K. Then, introducing the time constant $\tau = L/K$ in (10) leads to

$$I_{ph} = \frac{1}{1 + \tau\, s}\, I_{ph}{}^{*}. \tag{11}$$

Eq. 11 can be employed for the controller design. The value of L is chosen to satisfy the output current requirement in terms of residual ripple. The voltage V_{dc} must be greater then the maximum open-circuit voltage of the PV module.

4.2 Numerical Results

The proposed hardware model has been numerically tested with reference to a Shell SP150 photovoltaic solar module. The main characteristics of this panel are summarized in Table I.

Since the proposed hardware model has a reduced number of parameters, a preliminary trial and error procedure has been adopted to determine them, on the basis of the values evaluated for the circuit model, as described in Section 3.

In Fig. 4 are presented the simulation results, whereas Fig. 5 shows the corresponding *I-V* characteristics from the data sheet of the considered PV module. In particular, Fig. 4(a) shows the hardware model behavior at different irradiance levels: 1000÷600÷200 W/m^2, with the constant cell temperature of 25 °C. Each irradiance level is obtained by properly setting the current reference I_{ph}^* of the hardware model.

Fig. 4(b) shows the hardware model behavior at different cell temperatures: 60÷40÷20 °C with the constant solar irradiance of 1000 W/m^2. The different cell temperatures are obtained taking constant I_{ph}^* and varying only the resistances R_D and R_s of the hardware model.

The comparison between the model results and the data sheet characteristics shows a satisfactory agreement, even if the extracting procedure to obtain parameter values of the hardware model has not been optimized yet.

TABLE I
MAIN CHARACTERISTICS OF THE PV PANEL

Irradiance level 1000 W/m^2 at 25°C (AM 1.5)		
Cell type	*mono-crystalline silicon*	
Cells size/arrangement	125x125 mm / 72 series	
Rated power	P_r	150 W
Peak power	P_{MPP}	150 W
Open circit voltage	V_{oc}	34 V
Short circuit current	I_{sc}	4.8 A
Temperature coefficients		
α (P_{MPP})	-0.45% /°C	
α (V_{MPP})	-152 mV/°C	
α (I_{sc})	+2 mA/°C	
α (V_{oc})	-152 mV/°C	

5. CONCLUSIONS

A hardware model to represent the real behavior of PV modules is presented in this paper. The proposed hardware model allows realizing indoors an economic full-scale prototype of a PV generation system. Arbitrary transients or steady-state environmental parameters can be reproduced, despite of the external weather conditions. The hardware model has been preliminary tested by realistic numerical simulations, carried out by PSpice. The realization of a prototype is actually in progress in the Labs, and a complete set of experimental results is scheduled to be ready in few months.

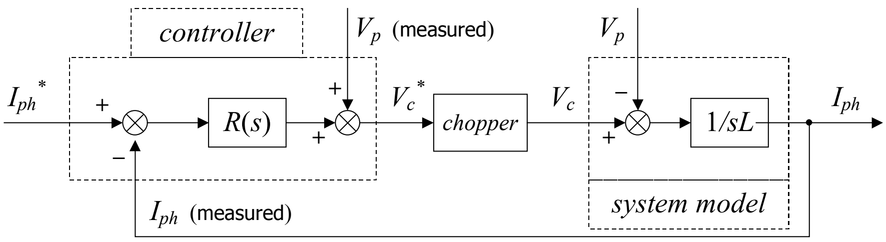
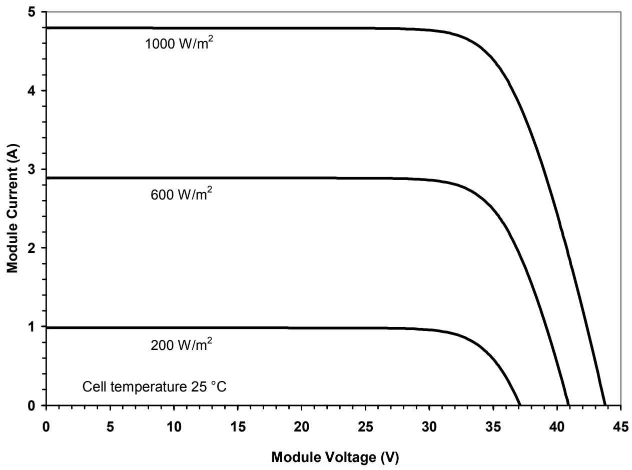
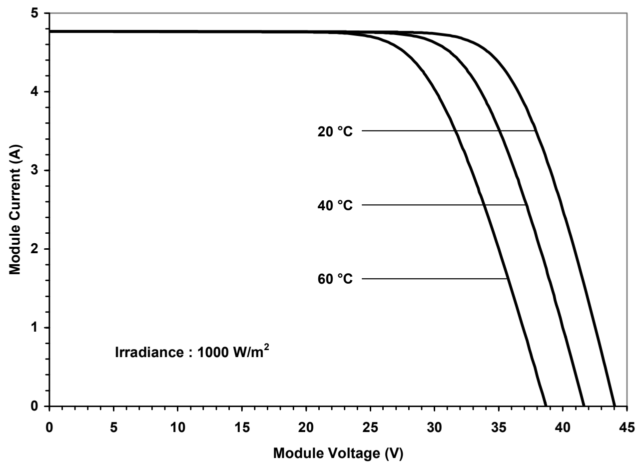


Fig. 3. Block diagram of the proposed current controller

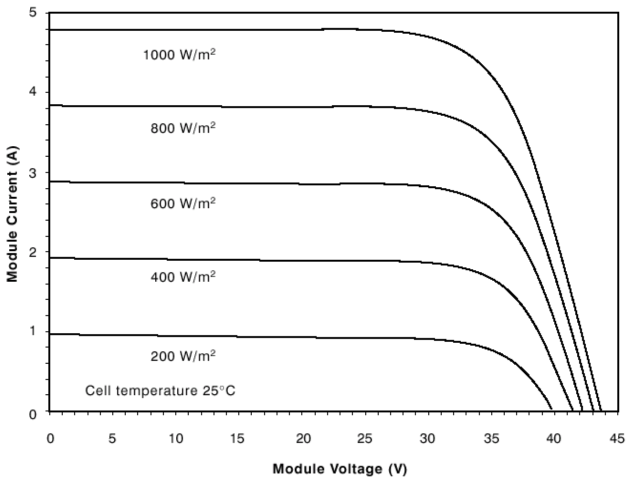


(a) - at various levels of irradiance

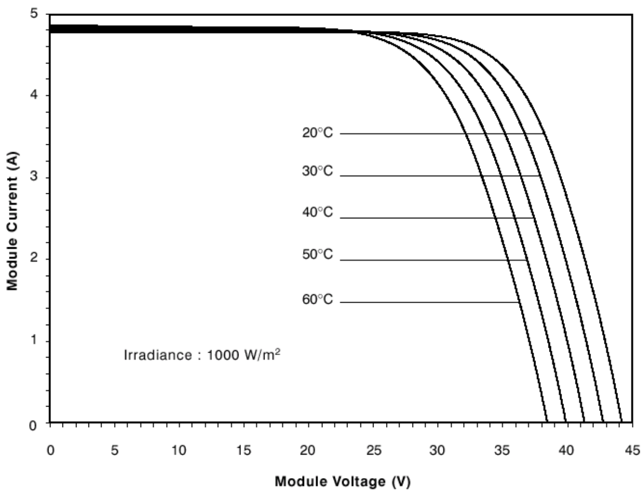


(b) - at various cell temperatures

Fig. 4. *I-V* characteristics of the hardware model (simulated).



(a) - at various levels of irradiance



(b) - at various cell temperatures

Fig. 5. *I-V* characteristics of the PV module (Shell Solar SP150 data sheet)

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