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PARAMETERS ESTIMATION FOR A MODEL OF PHOTOVOLTAIC PANELS

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Abstract – The paper describes the first results of a simulation and characterization tool useful to evaluate electrical performances of photovoltaic (PV) panels. A simple one-diode model is used in order to estimate the electrical parameters of a PV panel and predict how the *I-V* characteristic changes with environmental parameters such as temperature and irradiance.

This work is part of a wider project whose final purpose is to model a whole PV plant in order to control its performances in various environmental conditions and maximize the energy production. The continuous monitoring of a plant and the comparison between real and expected data will also greatly reduce the risk of out of order.

The used model is implemented as a MATLAB® script which yields the *I-V* and *P-V* characteristics of the PV panel under test. The model has been validated against an experimentally characterized PV panel. Some parameters of the model have been measured directly (irradiance and temperature) whereas others have been evaluated in two distinct ways: by means of direct computation on the data sheet or by means of best-fit on the measured data, and the results have been compared.

Keywords: Photovoltaic panel, mathematical model, simulation, Newton's method, optimization algorithm.

1. INTRODUCTION

Electricity production by renewable energy sources is actually promoted in many countries worldwide and is considered a strategic objective for the next years. Many founding programmes also support projects that provide potential utilities with access to renewable energy solutions and increase familiarity with renewable energy technologies. For these reasons, it is mandatory to improve the know-how and skills in this field.

Nowadays there is a lot of concern about photovoltaic systems because they can generate electricity on-site where it is needed, avoiding transport losses and contributing to CO_2 emission reductions in urban centres [1].

Knowledge of the characteristic of a PV panel is a pre-requisite for designing and dimensioning a PV power supply. This is the reason for the development of PV panel models useful for electrical measurement applications. This approach allows the development of new high-performances conversion systems balancing system-components and permitting the evaluation of the behavior of the entire system in various scenarios.

Generally speaking, PV devices (solar panels, inverters and loads) should be placed in a controlled-condition environment to test the performances of the whole system.

Alternatively, it is possible to develop simulations based on models of the PV panel. After the model has been estimated in given experimental conditions, it can be used to predict the PV panel operation under different working conditions (i.e. surface temperature of the PV panel, irradiance and weather conditions).

The simulation procedure can simulate steady-state and/or transient conditions so it is possible to focus the analysis on feasibility studies or on short-time performances. The simulation tool gives also the advantage of simulating different PV array sizes and the possibility to arrange virtually the panels or arrays as a network to analyze the behaviour and performances of a plant in a lot of possible configurations.

In section 2 the fundamentals properties of PV cells are summarized and mathematical models and basic parameters set are given. In section 3 the testing procedure and the parameters estimation technique are presented and the hardware is described. Finally in section 4 the estimation results are compared with experimental data.

2. MATHEMATICAL MODEL OF PV CELLS

Mathematical descriptions of the *I-V* characteristics of PV cells are available since many years and are derived from the physics of the p-n semiconductor junction.

A crystalline solar cell is, in principle, a large-area silicon diode. In the dark state, the *I-V* characteristic curve of this diode corresponds to the one of a normal p-n junction diode and it produces neither a voltage nor a current.

Illumination of the PV cell creates free charge carriers, which allow current to flow through a connected load. The so called photocurrent I_L is proportional to irradiance [2]. If the circuit is open the photocurrent is shunted internally by the p-n junction diode.

The simplest equivalent circuit of a PV cell (Fig. 1) is a current source whose intensity is proportional to the incident radiation, in parallel with a diode D and a shunt resistance R_{sh}. This resistance represents the leakage current to the ground. The internal losses due to current flow and the connection between cells are modelled as a small series resistance R_s [2].

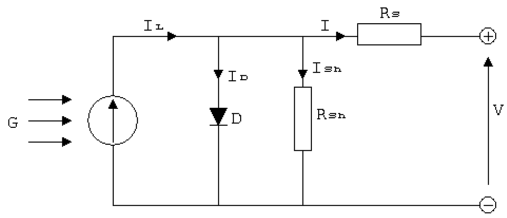

Fig. 1. Equivalent circuit of a PV cell.

The *I-V* characteristic is described by Equation (1), which shows the net current *I* of the cell as a function of the external voltage *V*; *n* is the well known ideality factor of the junction and its value ranges between 1 and 2.

$$I = I_L - I_0\left(e^{\frac{q(V+R_s\cdot I)}{n\cdot k\cdot T}} - 1\right) - \frac{V + R_s \cdot I}{R_{sh}} . \tag{1}$$

Other more accurate models are also available, such as a the two-diodes equivalent circuit (and the corresponding double-exponential equation), which is particularly suited for polycrystalline cells [3].

An closed-form exact solution of Equation (1) (or of the double-exponential equation) for the unknown current *I* is not available, hence numerical methods should be used to solve it. In this work the Newton-Raphson iterative method is exploited because it converges remarkably quickly, especially if the iteration begins sufficiently near the desired root.

There are many parameters in the model (1), as described in following subsections 2.1 and 2.2.

2.1. Whole model

Equation (1) in itself do not let to draw the *I-V* curve: the temperature dependence of the photo-current, the knowledge of open circuit voltage and of the saturation current is mandatory to complete the model [2]:

$$I_L(T) = I_L(T_{ref}) + \alpha(T - T_{ref}) \tag{2}$$

$$I_L(T_{ref}) = I_{SC}(T_{ref})\frac{G}{G_{ref}} \tag{3}$$

$$I_0(T_{ref}) = \frac{I_{SC}(T_{ref})}{\left(e^{\frac{q\cdot V_{OC}(Tref)}{n\cdot k\cdot T_{ref}}} - 1\right)} \tag{4}$$

$$V_{OC}(T) = V_{OC}(T_{ref}) + \beta(T - T_{ref}) , \tag{5}$$

where *G* is the irradiation, *k* the Boltzmann's constant, *q* the electron charge, *α* the temperature coefficient of the current and *β* the temperature coefficient of the voltage. The subscript *ref* identifies the Standard Test Conditions (STC) defined in the IEC 61215 international standard [4]; in particular $T_{ref} = 25\ °C$ and $G_{ref} = 1000\ W/m^2$. Moreover the short-circuit current $I_{SC}(T_{ref})$ and the open circuit voltage V_{OC} at STC are stated by the manufacturer so they are generally both known.

2.2. Initial estimation of resistance parameters

To complete the model we should know the values of R_{sh} and R_s. The R_s value has a marked effect on the *I-V* characteristic near the open circuit condition, while R_{sh} acts on the voltage of the maximum power point (MPP).

The initial estimation of these parameters, which we denote with R_{s0} and R_{sh0}, is critical because a bad starting point can compromise the convergence of the Newton-Raphson's method. The initial estimation will be improved as described in section 3.

A method for obtaining a first good estimation of R_s and R_{sh} was proposed by Gow and Manning [3], and consists in differentiating (1), evaluating it at open circuit conditions and rearranging it in terms of R_s. The obtained equation is

$$R_{s0} = -\left[\left.\frac{dV}{dI}\right|_{V=V_{OC}} + \frac{1}{X_V}\right], \tag{6}$$

where

$$X_V = I_0(T)\cdot\frac{q}{nkT}e^{\frac{qV_{OC}(T)}{n\cdot k\cdot T}} . \tag{7}$$

The initial value of R_{sh} is obtained by evaluating (1) at MPP conditions using the value of R_{s0} previously estimated:

$$R_{sh0} = \frac{V_{MP} + R_{s0}\cdot I_{MP}}{I_{MP} - I_L + I_0\left(e^{\frac{q\cdot(V_{MP}+R_{s0}\cdot I_{MP})}{n\cdot k\cdot T}} - 1\right)} . \tag{8}$$

The V_{MP} voltage and I_{MP} current at STC ,as well as other parameters present in Equations (6), (7) and (8) can be found on the PV panel or cell specifications. In particular, the value of $\left.dV/dI\right|_{V=V_{OC}}$ can be estimated on the reported *I-V* characteristic curve.

It is worth to highlight that R_s and R_{sh} are not affected by irradiance but only by physical characteristics of the cell such as its area and the fingers length.

3. TESTING PROCEDURE

Fig. 2 shows the conceptual diagram of the testing procedure of a PV panel; the cell's parameters can be inserted in the "PV panel data" section of the user interface. With these data, a first estimation of series and shunt resistances, R_{s0} and R_{sh0}, can be evaluated. In the characterization phase, the environmental parameters are obtained by means of sensors which measure the irradiance and the temperature of the panel surface: these parameters influence the current I_L.

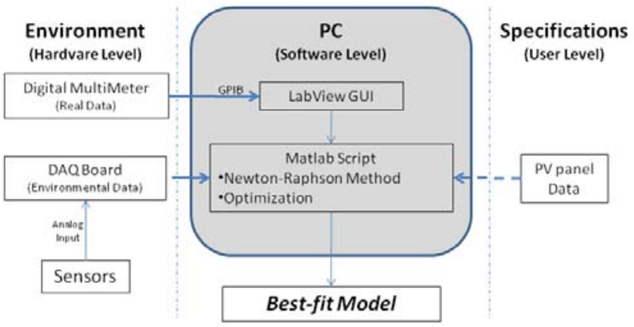

Fig. 2. Conceptual diagram of the testing procedure.

Two vectors of measured values of V and I are obtained by varying the load on the PV panel output terminals.

Similarly to [5], a MATLAB function has been implemented to determine, by means of the Equation (1) and the Newton-Raphson iterative method, the PV panel current I as a function of V for any set of model parameters. In this way, it is possible to compare the measured values of I with those predicted by the model (1), in two different cases:

1) *Initial model:* R_s is set to R_{s0} and R_{sh} is set to R_{sh0}. R_{s0} and R_{sh0} are determined by using the Equations (7) and (8).
2) *Best-fit model:* R_s and R_{sh} are determined by means of a best-fit over the measured data, which minimizes the sum squared error in the predicted values of I. The optimization process is based upon a gradient-based method which attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate [6]. In this way, starting with R_{s0} and R_{sh0} as initial values, we avoid the case of negative values for R_s and R_{sh}.

3.1. Hardware level

In order to validate the mathematical model a simple volt-ammeter method was used to collect real data as shown in Fig. 3.

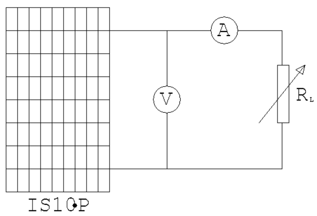

Fig. 3. Measurement circuit.

The voltage and current measures are acquired on the PC by means of an automated measurement system based on IEEE 488.2 instruments using a LabVIEW–based user interface. Environmental data are acquired using a Pt100 and a pyranometer, both interfaced to a DAQ board and processed by a MATLAB script which implements the mathematical model of the panel.

The I-V characteristic has been obtained applying the procedures described in the IEC 60904-1 international standard and in its normative references [7].

The Istar Solar IP10P PV panel was chosen to perform the characterization and modelling procedure; it consists of 2 parallel connected strings each composed by 36 series connected polycrystalline silicon cells and provides a peak output power of 10 W. The IP10P specifications at STC are listed in Table 1.

Table 1. IP10P specification at STC.

Parameter	Symbol	Value
Maximum Power (MP)	P_m	10 W
Voltage @MP	V_{MP}	17 V
Current @MP	I_{MP}	0.6 A
Open-circuit Voltage	V_{OC}	21,6 V
Short-circuit Current	I_{SC}	0.67 A
Nominal Voltage	V_n	12 V
$dV/dI\|_{V_{OC}}$		-0.5750

4. EXPERIMENTAL RESULTS

Fig. 4 shows the comparison between the measured I-V characteristics and the values predicted by the model in two cases: the resistances are estimated as R_{s0} and R_{sh0}; the resistances are estimated by means of best-fit.

It can be observed that if the measurement circuit of Fig. 3 is used, it is impossible to acquire points near the short circuit condition due to the additional resistances of the wires used to connect the PV panel to the measurement system. Besides, in these conditions the measures are degraded and the curve is very irregular. To avoid this drawback an electronic load should be used.

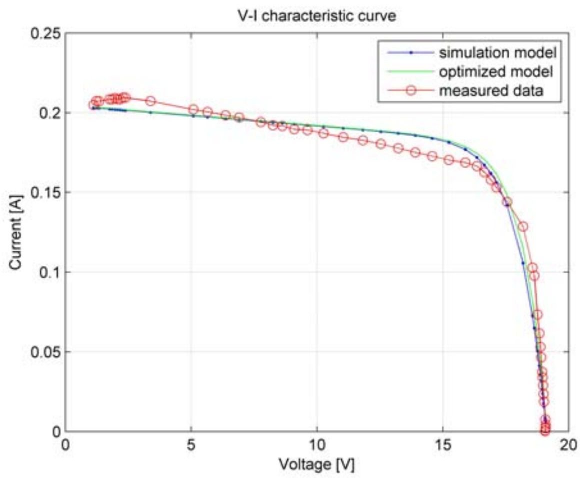

Fig. 4. I-V characteristic curve for IP10P at G = 300 W/m^2 and T= 27 °C.

In the same way, Fig. 5 shows the comparison between the measured *P-V* characteristic, and the characteristic obtained with the initial model and the best-fit model.

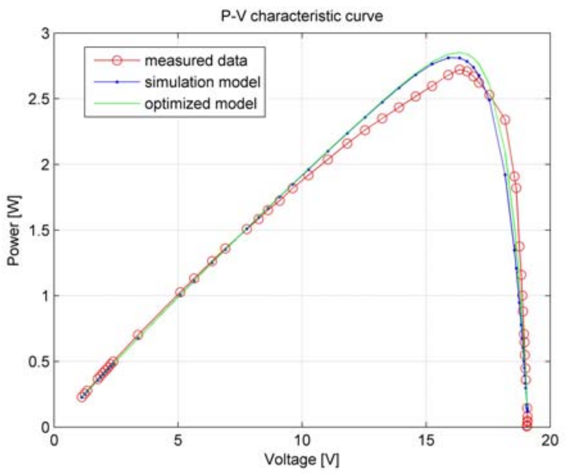

Fig. 5. P-V characteristic curve for IP10P @ G = 300 W/m^2 and T= 27 °C.

The experimental data used to plot graphs of Figs. 4 and 5 are acquired in low irradiance conditions due to the low power of the sunlight simulator.

Fig. 4 and Fig. 5 show a good agreement between the measured data and the model. Besides, there is only a little mismatch between the initial estimate and the optimized values for R_s and R_{sh} due to good initial estimation. In Table 2 some of results obtained with initial estimation and best-fit are summarized and compared with experimental data

Table 2. Estimated parameter for IP10P at G = 300 W/m^2 T = 33 °C.

Parameter	Measured	Initial	Best-fit
Series Resistance R_s	-	0,445 Ω	0,287 Ω
Shunt Resistence R_{sh}	-	38,59 Ω	38,594 Ω
Current @MPP I_{MP}	0,182 A	0,187	0,187 A
Maxium Power	2,44 W	2,39 W	2,46 W

5. CONCLUSIONS

An electrical model for a typical 10 Wp PV panel is estimated and tested. After measuring superficial temperature and irradiance and given the manufacturer specifications, the proposed tool estimates the two unknown parameters (series and shunt resistances) obtaining the best-fit of the measured *I-V* characteristic.

The simulation results are discussed demonstrating the feasibility of the proposed method. A MATLAB script permits to test PV panel performances and to verify the panel output under different load and weather conditions.

The main feature of the realized tool is the modularity so it is possible to simulate the behaviour of a complex photovoltaic plant imposing appropriate boundary conditions.

The described procedure can be of value for the electrical designer who wants to simulate steady-state conditions focusing the analysis on feasibility and on earning studies; moreover, comparisons between real data and the expected ones allows one to continuously verify the short-time performances of the plant, monitoring the decrease of performances and predicting the risk of out of order of PV plant.

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