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On the analytical approach for modeling photovoltaic systems behavior

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HIGHLIGHTS

- A method to calculate photovoltaic array equivalent circuit parameters is developed.
- This method is analytical, quick and accurate.
- It is based only on the information from manufacturer's datasheet.

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ABSTRACT

The 1-diode/2-resistors electric circuit equivalent to a photovoltaic system is analyzed. The equations at particular points of the *I*–*V* curve are studied considering the maximum number of terms. The maximum power point as a boundary condition is given special attention. A new analytical method is developed based on a reduced amount of information, consisting in the normal manufacturer data. Results indicate that this new method is faster than numerical methods and has similar (or better) accuracy than other existing methods, numerical or analytical.

1. Introduction

The use of renewable energy is a big concern in modern societies, and among the different sources, photovoltaic energy is one of the most relevant in terms of increase of installed power. This fact, together with other more specific applications (e.g. satellites and spacecraft), has led scientists to study the behavior of photovoltaic cells and the methods to optimize their power generation. From the middle of the twentieth century, descriptions of the mechanisms that rule the conversion of solar radiation into electric power have been published [1–6]. In addition, great efforts have been exerted to develop equivalent electrical/mathematical models to analyze the behavior of solar cells under different conditions, mainly different radiation levels and cell temperatures.

An electrical model consists in a simple circuit whose behavior fits the real behavior of a solar cell (see Figs. 1 and 2). The use of these circuit models, together with the correct definition of the electric parameters involved, is extremely important to maximize the power extracted from the cell working under real conditions. Also, the use of equivalent circuit models makes the simulation of more complex power systems that include solar cell panels possible. It should be pointed out that sometimes these power systems can have a very complicated behavior (e.g. in space applications these systems include batteries and programmed power consumptions, with important temperature gradients and different radiation levels affecting the output voltage of the solar panels, and must be optimized to ensure the survival of the satellite/spacecraft).

The photoelectric effect is responsible for transforming the radiation on the solar cells into electric energy. In general, the easiest way to characterize a solar cell is by considering a current source connected in parallel to an ideal diode (see Fig. 2a) [1,2,5].

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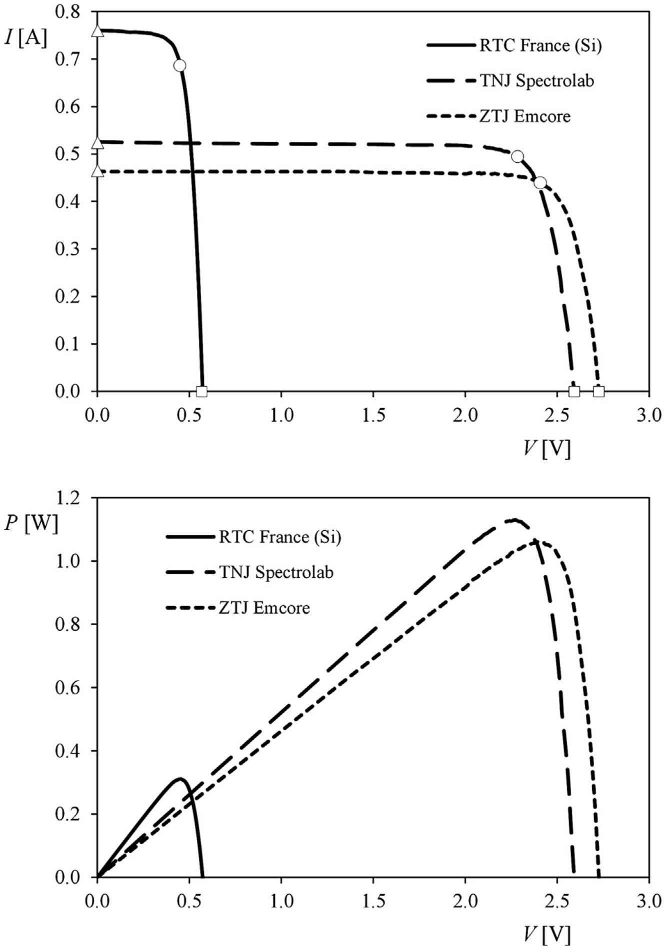

Fig. 1. Top: Current–voltage (I–V) curves of different solar cells: silicon (Si) cell from R.T.C. (La Radiotechnique Compelec, Paris, France), measured with 8096 microcomputer (Commodore, West Chester, Pennsylvania) at 33 °C [11]; TNJ triple-junction (GaInP2/GaAs/Ge) cell from Spectrolab (Sylmar, California, USA), measured at AM0 – 1353 W m^2– and 28 °C; and ZTJ triple-junction (InGaP/InGaAs/Ge) cell from Emcore (Albuquerque, New Mexico, USA), measured at AM0 –1353 W m^2– and 28 °C. In every curve short circuit (triangles), maximum power (circles), and open circuit (squares) points are indicated. Bottom: Power curve of these solar cells. Data from TNJ and ZTJ solar cells extracted from the manufacturer datasheets.

The equation that describes the behavior of the solar cell is then composed of two terms, one related to the source and the other to the p–n junction (which is, in fact, Shockley's ideal diode equation) [5]:

$$I = I_{pv} - I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]. \quad (1)$$

The first term of the expression above, I_{pv}, is the photocurrent delivered by the constant current source, the second term is the ideal recombination current from the diffusion and recombination of electrons and holes in p and n sides of the cell (Shockley diffusion theory), where I_0 is the reverse saturation current corresponding to it, T is the temperature and k is the Boltzmann constant. Finally, q is the charge of the electron. The last three constants are usually grouped into the so called thermal voltage, V_T:

$$V_T = \frac{kT}{q}. \quad (2)$$

To improve expression (1) and to better fit cell behavior, two resistors are usually added to the circuit (see Fig. 2c). One resistor (the shunt resistor, R_{sh}), represents the current leakage through the high conductivity shunts across the p–n junction and is added in parallel with the source and the diode. The other (the series resistance, R_s), is connected in series and represents the losses in cell solder bonds, interconnection, junction box, etc. [4,7]. Also, a non-dimensional constant, a, is added to the term of the recombination current in the p- and n-sides. This constant is called the ideality or quality factor (or sometimes emission coefficient), and it takes into account the deviation of the diodes from the Shockley diffusion theory (the value of this factor, a, is assumed to be constant and between 1 and 1.5 for one-junction cells [8,9], although some authors suggest that it depends on the ratio between the current, I, and voltage, V, of the cell [10]). The 1-diode/2-resistors circuit model is then defined by the expression:

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}. \quad (3)$$

Another change to the solar cell model was proposed in 1961 by Wolf and Rauschenbach [4]. These authors suggested that the I–V characteristics of silicon solar cell are more accurately represented by a double exponential expression (see Fig. 2d), the second exponential standing for the current from the recombination of electrons and holes in the depletion region, which dominates at lower forward-bias voltages. The behavior of the solar cell can be then translated into the following equation:

$$I = I_{pv} - I_{01}\left[\exp\left(\frac{V + IR_s}{a_1V_T}\right) - 1\right] - I_{02}\left[\exp\left(\frac{V + IR_s}{a_2V_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}, \quad (4)$$

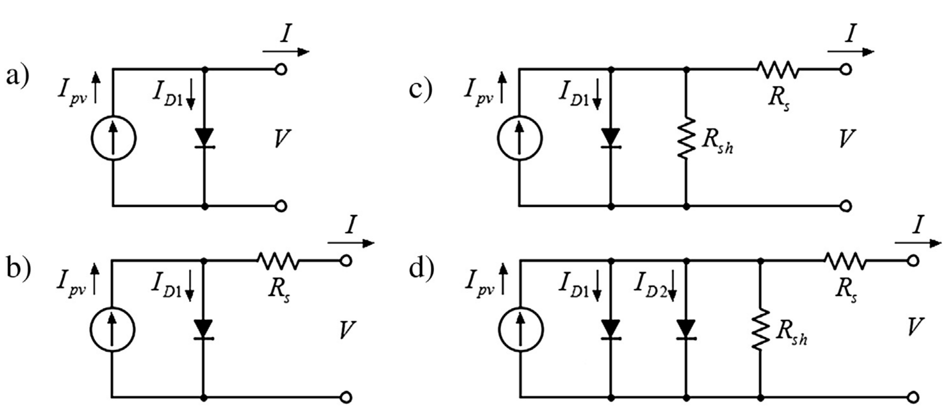

Fig. 2. Different circuit models to study the behavior of solar cells. (a) 1-diode; (b) 1-diode/1-resistor; (c) 1-diode/2-resistors; (d) 2-diodes/2-resistors.