Performance analysis of photovoltaic systems: research at IDR/UPM Institute

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***Abstract*—In this paper the work carried out at the IDR/UPM Institute on photovoltaic devices' performance is outlined. The aim of the work is to demonstrate the possibilities of the mathematical procedures developed beyond the space applications, in order to show them to other industrial sectors. The work carried out at the IDR/UPM Institute have been driven by selecting simple tools and procedures to model the solar cells/panels behavior, as modeling these photovoltaic devices is normally carried out by 1-Diode/2-Resistor equivalent circuit models, which might represent a unaffordable mathematical challenge for many professionals and technicians from the renewable energy sector.**

***Keywords*—solar cell, solar panel, photovoltaic device, performance, I-V curve**

I. Introduction

The UPMSat-2 project (see Fig.1), initiated in 2008 but officially started in 2011, has brought many research lines to *Instituto Universitario de Microgravedad "Ignacio Da Riva"* (IDR/UPM) from *Universidad Politécnica de Madrid* (UPM). Among these research lines it is possible to point out:

- Attitude Determination and Control Subsystems (ADCS's). The work of the IDR/UPM researchers has been driven towards control subsystems based on interaction with the Earth's magnetic field [1], [2].
- Thermal control subsystems. Mainly based on ESATAN analysis [3]–[5].
- Structural analysis of spacecraft and space instruments/systems [6]–[9].
- Spacecraft power subsystems. Devoted to photovoltaic systems (solar cells/panels) performance, harness design, and Li-ion batteries [10]–[20].

Besides, it should be also mentioned the impact of this project on the academic work carried out at the Aeronautics and Aerospace Engineering School (ETSIAE) from UPM. More precisely, apart from several Ph.D. thesis and dissertations, this project has represented the perfect framework to teach space systems engineering with a Project Based Learning (PBL) methodology [19], [21], [22].

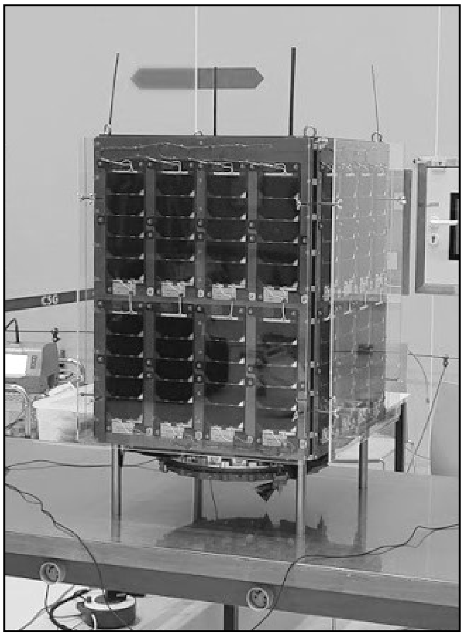

Fig. 1 Integration of the UPMSat-2 satellite at the Centre Spatial Guyanais of CNES (Kourou, French Guiana). February 2020.

Going back to the research line on spacecraft power subsystems, the work carried out in relation to solar cells/panels has been driven by a specific motivation, the use of analytical procedures to generate quick solutions in order accelerate early systems design. At IDR/UPM Institute, these analytical procedures have been implemented in the Concurrent Design Facility (CDF) for spacecraft mission design [23], [24], and in thermo-electric coupled analysis of satellite power subsystems with ESATAN.

Additionally, it should be also pointed out that a simple procedure for solar panel testing was developed to check the performance of the UPMSat-2 solar panels. Within this simple procedure, the solar panels are tested under the sun, the results being extrapolated to the common Standard Test Conditions (STC) for space photovoltaic systems (AM0 and 28 ºC) [17].

The aim of the present paper is to review the analytical and simple techniques related to photovoltaic systems performance analysis developed at the IDR/UPM Institute. The real possibility of using these techniques and procedures in other industrial sectors which deal with photovoltaic systems such as the renewable energy sector, or the construction sector, has driven us to write this work.

The present paper is organized as follows. In Section II, the main problem of modeling a solar cell/panel by using an equivalent circuit model is presented, whereas in Section III two analytical solutions defined at the IDR/UPM Institute are described. A simple and much simpler explicit methodology, equivalent to the analytical solutions described in Section III, is included in Section IV. Finally, conclusions are summarized in Section V. Additionally, an Appendix related to the Lambert function has been added in Section VI, as this function provides a very useful tool to solve explicit equations.

II. Solar cell/panel equivalen circuit model

There are several possibilities in relation to solar cell/panel equivalent circuit models. Among them, the one that is most regularly used in research is the 1-Diode/2-Resistor model (see Fig.2). The equation that relates the output current, I, to the output voltage, V, is the following [10]:

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V + IR_s}{naV_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} , \qquad (1)$$

in which the first term is the photocurrent, the second one is the current through the diode, and the third term represents the current through the shunt resistor (see Fig. 2). V_T is the thermal voltage ($V_T = \kappa T/q$; κ being the Boltzmann constant, T the temperature, and q the electron charge), a is the ideality factor of the diode, and finally n is the number of series-connected cells within the panel.

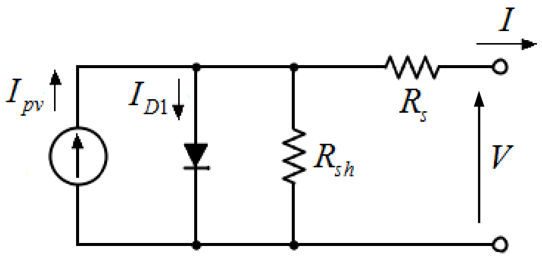

Fig. 2 Solar cell/panel 1-Diode/2-Resistor equivalent circuit.

The use of the aforementioned 1-Diode/2-Resistor equivalent circuit model by two important factors:

- On the one hand, the parameters of equation 1 (I_{pv}, I_0, a, R_s, and R_{sh}) should be calculated, in relation to both the solar irradiance, G, on the cell/panel and its temperature, T, before using this model.
- On the other hand, equation (1) is an implicit mathematical expression. Therefore, for a given value of the output voltage, V, the calculation of the corresponding output current, I, is not immediate, an iteration process being necessary.

There are several methodologies to extract the parameters of the 1-Diode/2-Resistor equivalent circuit model depending on the available information [25]–[31]. If the performance curve of the photovoltaic device (that is, the *I-V* curve, see Fig. 3) is known for certain values of irradiance and temperature, it is possible to fit equation (1) to the data. If only the characteristic points of the *I-V* curve (short circuit current, I_{sc}, open circuit voltage, V_{oc}, and current and voltage at maximum power point, I_{mp} and V_{mp}), are known, it is also possible to estimate the parameters of the model. Besides, as manufacturers normally give information on the variation of these characteristic points in relation to the irradiance and the temperature, it is possible to calculate the *I-V* curve for any combination of the mentioned irradiance and temperature values [32]–[37].

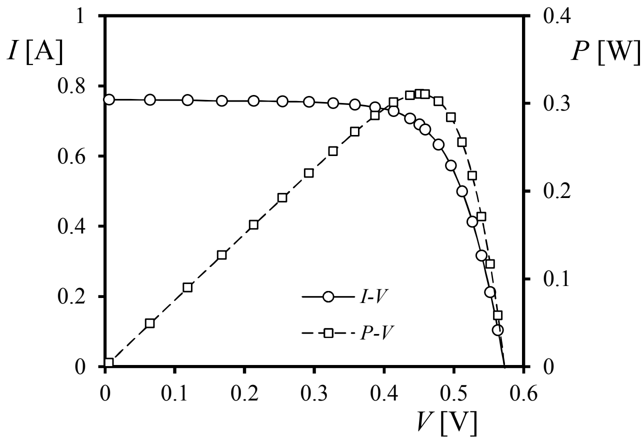

Fig. 3 *I-V* (current-voltage) and *P-V* (power-voltage) curves of a Si solar cell.

III. Analytical methodologies to extract the parameters of the 1-Diode/2-Resistor model

A. First methodology

If the current and voltage levels at the characteristic points (I_{sc}, V_{oc}, I_{mp} and V_{mp}) are known for certain values of the sun irradiance, G, and the temperature, T, it is possible to derive the following equations [10], [38]:

$$I_{pv} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} , \qquad (2)$$

$$I_0 = \frac{(R_{sh} + R_s) I_{sc} - V_{oc}}{R_{sh} \exp\left(\frac{V_{oc}}{naV_T} \right)} , \qquad (3)$$

$$\frac{naV_T V_{mp}\left(2I_{mp}-I_{sc}\right)}{\left(V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)\right)\left(V_{mp}-I_{mp}R_s\right)-naV_T\left(V_{mp}I_{sc}-V_{oc}I_{mp}\right)} = \exp\left(\frac{V_{mp}+I_{mp}R_s-V_{oc}}{naV_T}\right), \quad (4)$$

$$R_{sh}=\frac{\left(V_{mp}-I_{mp}R_s\right)\left(V_{mp}-R_s\left(I_{sc}-I_{mp}\right)-naV_T\right)}{\left(V_{mp}-I_{mp}R_s\right)\left(I_{sc}-I_{mp}\right)-naV_T I_{mp}}. \quad (5)$$

Once the above equations are obtained, the solution procedure is as follows:

- Estimate the ideality factor a. Its value is supposed to be within the bracket [1, 1.5] according to [37], [39].
- Obtain the value of R_s from equation (4).
- Obtain the value of R_{sh} from equation (5).
- Obtain the value of I_0 from equation (3).
- Obtain the value of I_{pv} from equation (2).

Once all parameters have been extracted equation (1) needs to be solved for the required values of the solar cell/panel output voltage. As said above, this requires a certain degree of skill solving mathematical implicit equations (by iterative methods or programing the appropriate computational tools, for example). Another way to solve the explicit equation is by using the Lambert function W_0 (see Appendix) [40]:

$$I=\frac{R_{sh}\left(I_{pv}+I_0\right)-V}{R_{sh}+R_s}-\frac{naV_T}{R_s}W_0\left(\frac{R_{sh}R_sI_0}{naV_T\left(R_{sh}+R_s\right)}\exp\left(\frac{R_{sh}R_s\left(I_{pv}+I_0\right)+R_{sh}V}{naV_T\left(R_{sh}+R_s\right)}\right)\right). \quad (6)$$

This methodology was successfully used by the researchers of the IDR/UPM Institute [10], [38], to fit the 1-Diode/2-Resistor equivalent circuit model to the well-known experimental data from [41]. The results obtained were among the best fittings methods found in the available literature [40], [42]–[48] in terms of non-dimensional RMSE (see Table I):

$$\xi=\frac{\mathrm{RMSE}}{I_{sc}}=\frac{1}{I_{sc}}\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(I_{calc,i}-I_i\right)^2}. \quad (7)$$

where $I_{cal,i}$ are the calculated currents and I_i are the measured currents from the experimental *I-V* curve.

B. Second methodology

The second methodology proposed is based on the negative branch of the Lambert function, W_{-1} (see Appendix). As solving equation (4) to obtain the value of R_s implies iteration, the following explicit equation is proposed [11]:

$$R_s=A\left(W_{-1}\left(B\exp\left(C\right)\right)-\left(D+C\right)\right), \quad (8)$$

where:

$$A=\frac{naV_T}{I_{mp}}, \quad (9)$$

$$B=-\frac{V_{mp}\left(2I_{mp}-I_{sc}\right)}{V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)}, \quad (10)$$

$$C=-\frac{2V_{mp}-V_{oc}}{naV_T}+\frac{V_{mp}I_{sc}-V_{oc}I_{mp}}{V_{mp}I_{sc}+V_{oc}\left(I_{mp}-I_{sc}\right)}, \quad (11)$$

$$D=\frac{V_{mp}-V_{oc}}{naV_T}. \quad (12)$$

The above equations were successfully applied to calculate the *I-V* curves of a photovoltaic device for different levels of irradiance and temperature [11].

TABLE I. BENCHMARK BETWEEN THE PROPOSED METHODOLOGY (CUBAS ET AL.) AND OTHER PARAMETER EXTRATION METHODS PROPOSED BY OTHER AUTHORS. COMPARISON BASED ON THE NON-DIMENSIONAL RMSE APPLIED TO THE DATA FROM THE PWP 201 SOLAR MODULE [41]. FROM [10]

Parameter extraction method	ξ
Cubas et al. (2014) [10]	$2.85\cdot10^{-3}$
Phang et al. (1984) [42]	$3.44\cdot10^{-2}$
Easwarakhanthan et al. (1986) [41]	$5.90\cdot10^{-3}$
AlHajri et al. (2012) [43]	$3.23\cdot10^{-3}$
Boudici et al. (2007) [44]	$3.89\cdot10^{-3}$
Al Rashidi et al. (2011) [45]	$6.02\cdot10^{-3}$
Wei et al. (2011) [46]	$3.61\cdot10^{-3}$
El-Naggar et al. (2012) [47]	$2.84\cdot10^{-3}$
Peng et al. (2013) [40]	$6.16\cdot10^{-3}$
Gong et al. (2013) [48]	$2.20\cdot10^{-3}$

IV. AN EXPLICIT METHOD AS AN ALTERNATIVE FOR THE 1-DIODE/2-RESISTOR MODEL

Explicit methods for describing solar cells/panels' performance have been developed as an alternative to the 1-Diode/2-Resistor equivalent circuit model. These methods consist of simple and explicit mathematical expressions that are more or less equivalent to equation (1), equation that defines de equivalent circuit model. As said before, these methodologies have proven to be a quite proper solution when a quick answer is required, or to be programed in some specific software environment such as ESATAN, in case of thermo-electric coupled analysis.

The following equation was proposed by IDR/UPM Institute researchers to be used instead equation (1):

$$I=\begin{cases} I_{sc}\left(1-\left(1-\frac{I_{mp}}{I_{sc}}\right)\left(\frac{V}{V_{mp}}\right)^{\frac{I_{mp}}{I_{sc}-I_{mp}}}\right) & ;\ V\le V_{mp} \\ I_{mp}\left(\frac{V_{mp}}{V}\right)\left(1-\left(\frac{V-V_{mp}}{V_{oc}-V_{mp}}\right)^{\phi}\right) & ;\ V\ge V_{mp} \end{cases}. \quad (13)$$

This expression only depends on one parameter, ϕ, which can be approximated by using the current and voltage at the characteristic points as:

$$\phi = \left(\frac{I_{sc}}{I_{mp}}\right)\left(\frac{I_{sc}}{I_{sc}-I_{mp}}\right)\left(\frac{V_{oc}-V_{mp}}{V_{oc}}\right), \qquad (14)$$

Nevertheless, if the current and voltage values, I^* V^*, of a point from the *I-V* curve between V_{mp} and V_{oc} are available, it is possible to derive an exact solution for ϕ:

$$\phi = \frac{\ln\left(V_{mp}I_{mp}-V^*I^*\right)-\ln\left(V_{mp}I_{mp}\right)}{\ln\left(V^*-V_{mp}\right)-\ln\left(V_{oc}-V_{mp}\right)}, \qquad (15)$$

In Fig. 4, the fitting of equation (13) to the data of a Si solar cell from is shown, together with the fitting of equation (1), that represent the mathematical expression of the 1-Diode/2-Resistor equivalent circuit model. As it can be observed, the explicit equation defined at the IDR/UPM Institute perfectly matches the experimental data. Furthermore, if the non-dimensional RMSE are compared (equation (7)), the value corresponding to the explicit equation, $\xi = 0.0041$, is quite reduced, although the one from 1-Diode/2-Resistor equivalent circuit model is logically better, $\xi = 0.0009$. Nevertheless, if the scope of interest is reduced to a region close to the Maximum Power Point, the difference between the results from both models is reduced ($\xi = 0.0014$ and $\xi = 0.0007$, respectively) [20].

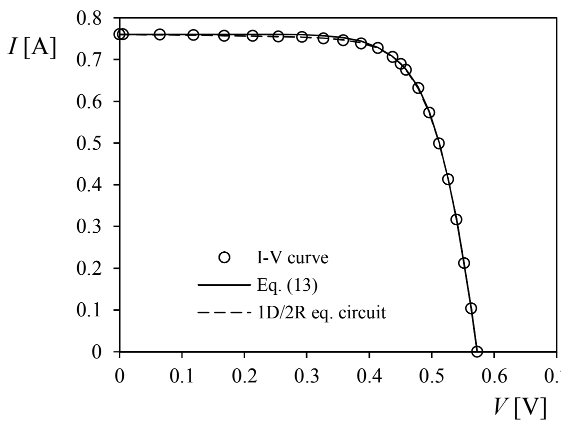

Fig. 4 Explicit equation (13) fitted to the *I-V* curve from RTC France Si solar cell [41]. The equivalent 1-Diode/2-Resistor equivalent circuit model, equation (1) has been also fitted to the data.

V. CONCLUSIONS

In the present work the methodologies developed at the IDR/UPM Institute to analyze photovoltaic technologies from space systems are summarized. In brief, the methodologies described are the following:

- Analytical methodologies to ease the use of the 1-Diode/2-Resistor equivalent circuit model.
- An explicit method that can replace the 1-Diode/2-Resistor equivalent circuit model.

Both require minimum mathematical skills, and limited initial data (the characteristic points of the *I-V* curve).

The aim of this work is to transfer these methodologies to other industrial sectors that involve photovoltaic technologies, such as the renewable energy sector. Also, the purpose of the present work is to encourage engineers and technicians from these industrial sectors, to use the simple methodologies described above in the power estimations they could carry out.

VI. APPENDIX

The Lambert function, $W(z)$ is defined with the following expression:

$$z = W(z)\exp\left(W(z)\right), \qquad (16)$$

where z is a complex number. For a real variable x, the Lambert function is defined within the bracket [−1/e, ∞], having a double value for negative values of the variable x. In order to solve possible conflicts, two different branches are defined for this function $W_0(x)$, for $W(x) \geq -1$, and $W_{-1}(x)$, for $W(x) \leq -1$. Besides, the branch $W_0(x)$ is usually divided into two sections that can be better approached separately $W_0^-(x)$, for $W_0(x) \leq 0$, and $W_0^+(x)$, for $W_0(x) \geq 0$. This function represents a worthy strategy to solve some equations that involve exponentials, as if $X = Y\exp(Y)$ then $Y = W(X)$.

The following approximations have been found in the literature to this function [49]:

$$W_0^-(x) = -1 + \frac{\sqrt{\varphi}}{1+\left(\left(N_1\sqrt{\varphi}\right)/N_2+\sqrt{\varphi}\right)}, \qquad (17)$$

where:

$$\varphi = 2(1+ex),\ N_1 = \left(1-\frac{1}{\sqrt{2}}\right)\left(N_2+\sqrt{2}\right), \text{ and}$$

$$N_2 = 3\sqrt{2}+6-\frac{\left(2237+1457\sqrt{2}\right)e-4108\sqrt{2}-5764}{\left(215+199\sqrt{2}\right)e-430\sqrt{2}-796}\varphi \qquad (18)$$

$$W_0^+(x) = 1.4586887\ln\left(\frac{1.2x}{\ln\left(2.4x/\ln(1+2.4x)\right)}\right) - 0.4586887\ln\left(\frac{2x}{\ln(1+2x)}\right), \qquad (19)$$

$$W_{-1}(x) = -1-\sigma-5.95061\left(1-\frac{1}{1+f(\sigma)}\right), \qquad (20)$$

where:

$$f(\sigma) = \frac{0.23766\sqrt{\sigma}}{1-0.0042\sigma\exp\left(-0.0201\sqrt{\sigma}\right)}, \text{ and}$$

$$\sigma = -1-\ln(-x). \qquad (20)$$

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