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Technical Note

Simple estimation of PV modules loss resistances for low error modelling

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ABSTRACT

For practical purposes it can be assumed that the power delivered by a photovoltaic generator that is connected to an MPPT is always maximal. When studying the behaviour of a PV generator working in this way, the most interesting aspect is the evolution of the point of maximum power. So, the analysis of the I-V characteristic must be centred in the area of high voltages. In this situation the five parameter model is very appropriate for characterizing the PV generator.

On the other hand, in the case of photovoltaic modules the information currently provided by manufacturers is insufficient to do modelling. Thus, to evaluate the loss resistances it is necessary to use any of the different methods that currently exist.

The purpose of this paper is to present a new procedure, based on simplified equations, which allows the estimation of the loss resistances of any PV crystalline silicon module. By simulating the modules with the loss resistances calculated in this way highly accurate results are obtained. Especially in the surrounding of the maximum power point the error is always less than 0.5%.

1. Introduction

For practical purposes it can be assumed that the power delivered by a photovoltaic generator that is connected to an MPPT is always the highest. If it is wished to study the behaviour of a PV generator in that situation, the most interesting aspect is to know the evolution of the maximum power point. Then, the analysis of the characteristic I-V will focus on the part where voltages are high. From a simulation point of view this detail is important, because it must be ensured that the response of the model in that area is optimal.

In this situation the five parameter model is a very appropriate choice. Firstly, because most times the results have a high degree of consistency with experimental data [1–3] and secondly, as they are not too complex it is relatively simple to implement and analyse them [1,3,4].

On the other hand, it must be borne in mind that the complexity of a model in itself does not guarantee its reliability. It also depends on the quality with which the data or basic parameters required are determined. If the uncertainty about them is considerable, it will be difficult to trust the results.

In the case of photovoltaic modules the information provided by manufacturers is insufficient for doing the modelling. As is known, in order to complete data, what is often done is to make an a priori estimation of any parameter. In many cases the parameter is the ideality factor, which is firstly assigned a value [5–7], and from this the values of the loss resistances are obtained.

However, evaluating the loss resistances is not easy, proof of which is the large number of papers describing or mentioning procedures to obtain them more or less accurately [3,5–10]. In general, simple methods lead to rough, unreliable results. To the contrary, methods that offer good results are based on complex equations [6,7] or are based on experimental data and its statistical treatment [9,10]. In both cases solutions are not so easy to reach without the help of a computer.

The purpose of this paper is to present a simple procedure, based on simplified equations, which will allow the loss resistances of any crystalline silicon module to be estimated. As an example, the resistance values calculated in this work have been obtained using a normal non-programmable scientific calculator.

The data required for calculations are those appear in any catalogue of modules (I_{SC}, I_{MP}, V_{OC} and V_{MP}). Although equivalent data obtained through test can also be used. Once the values of loss resistances are known, it is possible to trace the I-V curve with great accuracy. In all the cases studied the difference between the manufacturer's data and the results of the simulations was always less than 0.5%.

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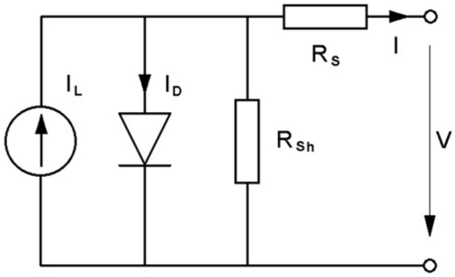

Fig. 1. Equivalent circuit for PV cells.

2. Model and equations used

As previously mentioned, the modelling of PV cells and modules can be carried out by means of equations that provide different degrees of approximation to the real device. In this paper the one exponential model for PN junction has been chosen (five parameters). Fig. 1 shows the equivalent circuit. The equation that describes its behaviour is:

$$I = I_L - I_0 \cdot \left[\exp\left(\frac{V + I \cdot R_S}{n \cdot V_{th}}\right) - 1\right] - \frac{V + I \cdot R_S}{R_{Sh}} \quad (1)$$

where I_L is the photocurrent, I_0 the reverse saturation current of the diode, n the "ideality factor", R_S and R_{Sh} the series and shunt resistances and V_{th} the "thermal voltage" of a cell.

By applying the short circuit conditions to equation (1), I_L can be obtained as:

$$I_L = \frac{I_{SC} \cdot (R_S + R_{Sh})}{R_{Sh}} + I_0 \cdot \left(\exp\frac{I_{SC} \cdot R_S}{n \cdot V_{th}} - 1\right) \quad (2)$$

Most times I_L is simplified by:

$$I_L \approx \frac{I_{SC} \cdot (R_S + R_{Sh})}{R_{Sh}} \quad (3)$$

In the same way, the open circuit conditions lead to an equation for I_0:

$$I_L = I_0 \cdot \left(\exp\frac{V_{OC}}{n \cdot V_{th}} - 1\right) + \frac{V_{OC}}{R_{Sh}} \quad (4)$$

Substituting equation (2) in (4) and after some approximations:

$$I_0 \approx \frac{I_{SC} \cdot (R_S + R_{Sh}) - V_{OC}}{R_{Sh}} \cdot \exp\left(-\frac{V_{OC}}{n \cdot V_{th}}\right) \quad (5)$$

In the above equations it should be noted that I_0 and V_{th} are functions of the temperature, given by:

$$I_0(T) = C \cdot T^3 \cdot \exp\left(-\frac{V_{GO}}{n \cdot V_{th}}\right) \quad (6)$$

$$V_{th}(T) = \frac{k \cdot T}{q} \quad (7)$$

In these last equations V_{GO} is the silicon gap, C is a constant that can be obtained from standard test conditions (STC), k the Boltzmann constant, T the absolute temperature of the cells and q the electron charge.

For a given irradiance and temperature, equation (1) supports different combinations of n, R_S and R_{Sh} whose I-V curves pass through the same points of I_{SC}, V_{MP}, I_{MP} and V_{OC}. Taken separately, these values of n, R_S and R_{Sh} are not relevant. What really makes them significant is the relationship formed by the three parameters [11].

Normally, for crystalline silicon PV modules this model requires an ideality factor between 1 and 1.3 [12]. Nevertheless, different studies have shown that $n = 1$ is adequate for modelling purposes [4,6,12]. So, in this work it will be taken that $n = 1$.

Once all the parameters are known the simulation of the equivalent circuit using these equations is quite straightforward. As an example, in this work all the simulations were made with Matlab–Simulink.

3. Characterization of the modules studied

Table 1 contains the catalogue data of the four modules used in this study. The effect of deviations between actual and conventional values, due to tolerances or other causes is not taken into account. At all times it is assumed that their experimental I-V curves (STC) verify the specified points.

Also in the same Table are the values of the loss resistances to be fitted to the models so that their I-V curves contain the given points. These resistances have been calculated using the equations that are proposed later. No account is taken of their possible dependence on temperature or irradiance. Within the normal operation range of the modules such simplifications do not lead to important differences in the experimental data [7,12,13].

The modules have been selected with the intention of making this study was as general as possible. To achieve this, they have been chosen so that their data is very different. However, although sometimes the data seem very different, it may happen that two modules are very similar, or even become equivalent (or any of its parameters).

One way to check if there are significant differences between different PV modules, generators, etc, is normalizing their values by conducting a base change. The "base" magnitudes chosen here are $I_B = I_{SC}$ and $V_B = V_{OC}$ from each module. The derived power base is $P_B = I_{SC} \cdot V_{OC}$. So, the "normalized" maximum power takes the same value that the fill factor. Finally, the base resistance is $R_B = V_{OC}/I_{SC}$.

The proposed changes convert all the magnitudes in "per unit, pu" values. This is the most usual way to make comparisons in the field of Electrical Engineering. This transformation avoids any reliance on specific values, number or size of cells, etc, and makes the data be completely general [14].

Table 2 contains data in "pu" values. It can be seen now that two modules have very similar series resistances. The same occurs with their maximum power voltages. Also, the module with lower r_S (pu) has the largest v_{MP} (pu), and vice versa. These results and comparisons have been possible by the use of "pu" values and the base magnitudes chosen. This would not be so easy if the normalization were made using other base magnitudes.

Table 1
Data from catalogues (STC) and estimated loss resistances (for $n = 1$).

Modules	No cells	V_{OC} (V)	I_{SC} (A)	V_{MP} (V)	I_{MP} (A)	P_{MP} (W)	R_S (Ω)	R_{Sh} (Ω)
AP 165	54	32.0	7.40	25.0	6.60	165	0.4676	61.8
ATERSA A 120	36	21.0	7.70	16.9	7.10	120	0.2030	91.2
ISOFOTON I-110	72	43.2	3.38	34.8	3.16	110	0.9608	916
BP 5170 S	72	44.2	5.00	36.0	4.72	170	0.5840	1965