

Photovoltaic Module Parametric Identification

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Abstract—Photovoltaic modules parametric identification is often performed based on data available in the data sheet and referred to standard test conditions. On-line identification is trickier when irradiance and temperature sensors are not available. In this paper, an identification procedure is presented aiming to identify some module fault conditions that often occur during its lifetime. The proposed approach is applied to a large database of current vs voltage curves that are experimentally measured on a real photovoltaic plant.

Index Terms—diagnosis, parametric identification, photovoltaic systems.

I. INTRODUCTION

Photovoltaic (PV) modules electrical behavior is described by using the Single Diode Model (SDM), which gives a good tradeoff between accuracy and complexity. It is shown in Fig.1.

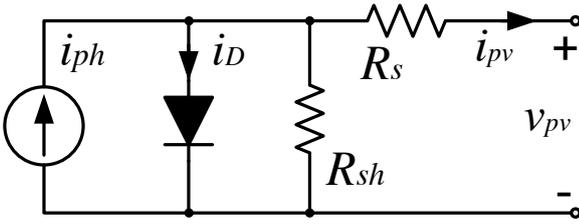


Figure 1. PV module SDM.

This model gives a relation between the PV current and the PV voltage that is non linear and also implicit. Nevertheless, in literature it is shown that a useful expression of the PV current i_{pv} as an explicit function of the PV voltage v_{pv} is available by using the Lambert W-function [1]:

$$i_{pv} = \frac{R_{sh}(I_{ph} + I_s) - v_{pv}}{R_s + R_{sh}} - \frac{a}{R_s} W(\theta) \quad (1)$$

wherein:

$$\theta = \frac{R_s R_{sh} I_s}{a(R_s + R_{sh})} e^{\frac{R_s R_{sh}(I_{ph} + I_s) + R_{sh} v_{pv}}{a(R_s + R_{sh})}} \quad (2)$$

and

$$a = \frac{N_s \eta k T}{q} \quad (3)$$

The five parameters $\{I_{ph}, I_s, \eta, R_s, R_{sh}\}$, that appear in (1) and (2), are the photo induced current, the saturation current, the ideality factor, the series and the shunt resistances, respectively. Instead, N_s is the number of series connected

cells in the PV module, which is known from the module datasheet. The constants k and q are the Boltzmann constant and the electron charge, respectively.

The values of the five parameters are usually determined in Standard Test Conditions (STC) on the basis of PV module operating data taken from the data sheet. Indeed, the values of the open circuit voltage and of the short circuit current, their thermal coefficients, as well as the voltage and the current at which the maximum power point occurs are commonly used in literature [1]. The parametric identification in STC, although not trivial, is simplified by the fact that the PV cells operating irradiance, $G_{STC} = 1000 \text{ W/m}^2$, and temperature, $T_{STC} = 25^\circ\text{C}$, are known.

Many approaches to the PV SDM parametric identification in STC have been published in literature. Some of them, e.g. [2], use a number of points describing the current vs. voltage (I - V) curve, thus their input is not limited to the data available in the data sheet. Other authors investigate the use of an optimization algorithm for determining the set of the five parameters that minimizes the difference between the model and the current/voltage measured couples available. Usually the function to be minimized is the Root Mean Square Error (RMSE). Examples of such approaches can be found in [3]-[8]. The equation (1) and the relationships among the SDM parameters and the experimental data are often used for bounding the search space or to fix a suitable guess solution in order to improve the convergence rate of the algorithm and reduce its computational effort. Such approaches are more oriented to an off-line identification, because of the difficulty of running an optimization algorithm through an embedded system, with limited memory and processing resources. Instead, for the on-site applications, the approaches presented, e.g., in [9] and [10] seem to be more suitable, because they use straightforward formulae relating experimental data to SDM parameters values, so that a limited computational effort is required. The price to pay is the higher RMSE, with respect to approaches based on the use of an optimization algorithm, which keeps limited to a reasonable value for the on-site uses.

Unfortunately, in normal outdoor operation, parametric identification becomes more tricky, because the irradiance and temperature data are not always available. Indeed, the on-field measurement of the module irradiance and temperature is expensive and often impractical, especially when the PV array includes many modules. Nevertheless, the parametric identification of the PV module or string in outdoor conditions is very useful for diagnostic purposes (see e.g. [11]). Thus, numerical approaches that can be even implemented by using cheap embedded systems are very interesting for on-field implementation.

In this paper a possible approach to the on-field identification of the working parameters of a PV module is

presented. The approach takes as input the I - V curve of the PV module acquired in a number of voltage samples. The identification results are related to I - V curves that are experimentally acquired at the PV plant of the Tampere University in Finland. Experimental measurements are analyzed by applying novel results and methodologies presented in the recent literature. Application of the proposed method to identify the increase of the series resistance R_s appearing in the SDM of the PV module is also envisaged.

The paper is organized as follows. In Section II a description of the proposed numerical approach is given. Afterwards, in Section III it is shown how it works and what are the results achieved by working on real experimental data. Section IV summarizes the conclusions and the future work.

II. THE IDENTIFICATION PROCEDURE

Although the unknown parameters are $\{I_{ph}, I_s, \eta, R_s, R_{sh}\}$, it has to be taken into account that the photo induced current and the saturation current are, in turn, dependent on the actual operating irradiance and temperature values, $\{G, T\}$, which are unknown too. Thus, the following dependencies of the two currents from G and T are exploited, in addition to (3), in order to replace I_{ph} and I_s with G and T in the list of parameters:

$$I_{ph} = I_{ph,STC} \frac{G}{G_{STC}} \left[1 + \alpha_l (T - T_{STC}) \right] \quad (4)$$

$$I_s = C_{STC} T^3 e^{-\frac{E_g(T)}{kT}}, \quad (5)$$

where α_l is the thermal coefficient of the panel short circuit current and all the quantities having the subscript STC are referred to the Standard Test Conditions [1]. $E_g(T)$ is the material band gap at the temperature T , which is determined as [12]:

$$E_g(T) = E_{g,STC} \left[1 + \alpha_E \cdot (T - T_{STC}) \right], \quad (6)$$

wherein the thermal coefficient of the energy gap is assumed to be equal to $\alpha_E = 0.000277 \text{ K}^{-1}$.

By using (4), (5) and (6) it is evident that the identification of the two parameters $\{I_{ph}, I_s\}$ is replaced by the couple $\{G, T\}$, so that the set to identify is $\{G, T, \eta, R_s, R_{sh}\}$.

In order to reduce the cardinality of this set, the ideality factor η has been kept constant, which is an assumption that is in line with the literature [12]. Finally, the set of parameters to identify for a given I - V curve is $\{G, T, R_s, R_{sh}\}$. The identification is performed by the function *fit.m* in Matlab. A procedure described in [1] and using explicit formulae is used to calculate the required guess solution referring to the STC data. Any other procedure, e.g. described in [1]-[10] should be used, without affecting the result of the on-site identification proposed in this paper. It has been decided to use the approach in [1] based on explicit formulae because of the possibility of applying the whole process described in this paper for on-site identification purposes.

III. EXPERIMENTAL RESULTS

The experimental results are based on I - V curve measurements acquired at the PV plant installed on the roof of the Tampere University in Finland. The curves are acquired by sampling the voltage interval $[0, V_{oc}]$ of a single PV module in 4000 values. The panel is a NAPS NP190GKg, including 54 poly-crystalline silicon cells.

In Table I the guess solution, in STC, and the ranges of the parameters used in the *fit.m* procedure are listed. The parameter η has been fixed at $\eta_{STC} = 1.0686$.

Table I. Guess solution and search space of the parameters to identify.

Parameter	Guess solution	Range
$G \text{ [W/m}^2\text{]}$	1000	[10,1300]
$T \text{ [}^\circ\text{C]}$	25	[0,70]
$R_s \text{ [}\Omega\text{]}$	0.3786	[0.1,5]
$R_{sh} \text{ [}\Omega\text{]}$	122.56	[50,500 k]

The first test refers to two I - V curves acquired at different irradiance levels. The fitting curves achieved for the two cases are given in Fig. 2 and in Fig. 3. From the latter one it is possible to appreciate the very good quality of the fitting curves given by the equation (1) and the SDM also in the region where the experimental measurements were more affected by the noise, thus close to the open circuit voltage. Tables II and III give the sets of four parameters corresponding to the two interpolating curves shown in Fig. 2 and in Fig. 3. The 95% confidence bounds are also reported. They reveal that the accuracy of identification of the shunt resistance value is not the same as for the other three parameters. Especially, at low irradiance level the fitting procedure searches for the R_{sh} value achieving the absolute minimum of the RMSE between the SDM (1) and the experimental I-V data in a wide region. By comparing the fixed range of R_{sh} (third column in Table I) with the identified value of that parameter given in Table II, it is evident that, for the lowest irradiance value tested, the identified value is close to the upper bound. The confidence interval is so wide to reveal that the influence of the R_{sh} parameter in that case is negligible with respect to the others.

The results are in line with the ones presented in the recent literature, concerning the possibility of scaling down the SDM when actual operating conditions occur. In [13] and [14] it has been demonstrated that two indicators, named γ_I and γ_V , that give the relationships between the MPP coordinates, the short circuit current and the open circuit voltage, have been used to define a novel coefficient, named Series Parallel Ratio *SPR*.

Table II. Identified set of parameters and confidence intervals for the example I - V curve at medium irradiance.

Parameter	Identified Value	95% Conf. Bound
$G \text{ [W/m}^2\text{]}$	580.8	[580.3,581.3]
$T \text{ [}^\circ\text{C]}$	49.1	[49.0,49.1]
$R_s \text{ [}\Omega\text{]}$	0.7954	[0.7923,0.7985]
$R_{sh} \text{ [}\Omega\text{]}$	494.4 k	[-98.09 M,99.08 M]

Table III. Identified set of parameters and confidence intervals for the example I - V curve at high irradiance.

Parameter	Identified Value	95% Conf. Bound
G [W/m^2]	937.8	[936.8,938.7]
T [$^{\circ}\text{C}$]	49.3	[49.3,49.3]
R_s [Ω]	0.775	[0.7731,0.7768]
R_{sh} [Ω]	225.6	[195.1,256.1]

In formulae [3]:

$$\gamma_I = \frac{I_{MPP}}{I_{SC}} \quad (7)$$

$$\gamma_V = \frac{V_{MPP}}{V_{OC}} \quad (8)$$

$$r = \frac{\gamma_I(1-\gamma_V)}{\gamma_V(1-\gamma_I)} \quad (9)$$

$$SPR = \frac{1-\gamma_I}{e^{-r}} \quad (10)$$

The SPR , as well as γ_I and γ_V , has been previously used in literature for the identification of the SDM parameters in STC. Moreover, these indicators might be of interest also for detecting the progressive increase of the series resistance or decrease of the shunt resistance in the SDM caused, for example, by aging. It is known [14] that the SPR gives an aggregate information about the role of these two resistances, which cannot be obtained from the analysis of the Fill Factor and so on. Indeed, as it is shown in [14], if $SPR > 1$, the shunt resistance can be settled to an infinite value, while, when $SPR < 1$, the series resistance is negligible. Fig. 4 and Fig. 5 show the result of the identification process of γ_I and γ_V performed on experimental I - V curves obtained from the same PV module, to which also three different additional series resistances have been added. The consequent effect on γ_V is recognizable and relevant, especially at a high irradiance level. The resulting effect on the SPR is even more evident, because a non-monotonic behavior with the increasing irradiance is achieved, as shown in Figure 6. This aspect is under further investigation from the theoretical point of view.

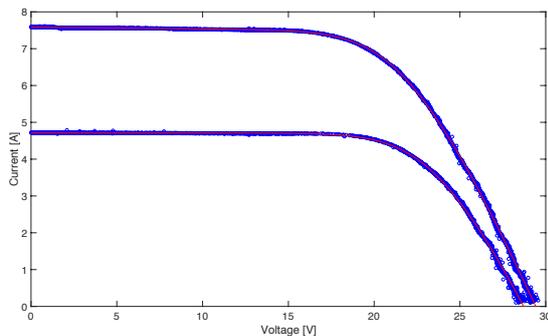


Figure 2. Experimental I - V points (blue markers) and fitting curves (in red color) at high and low irradiances.

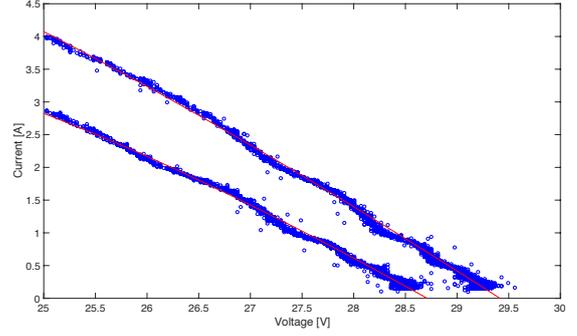


Figure 3. Detail of the results shown in Fig. 2 in proximity of the open circuit voltage.

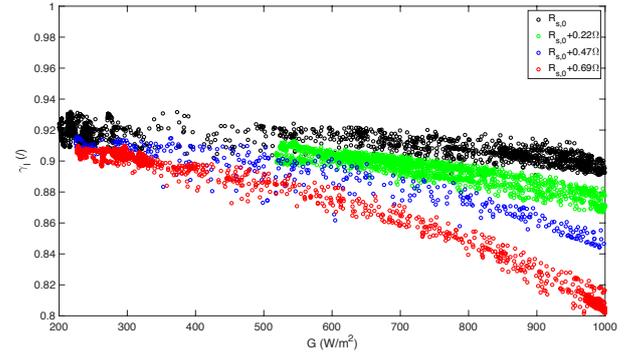


Figure 4. Identified γ_I as a function of irradiance. $R_{s,0}$ is the series resistance of the PV module without any additional resistor.

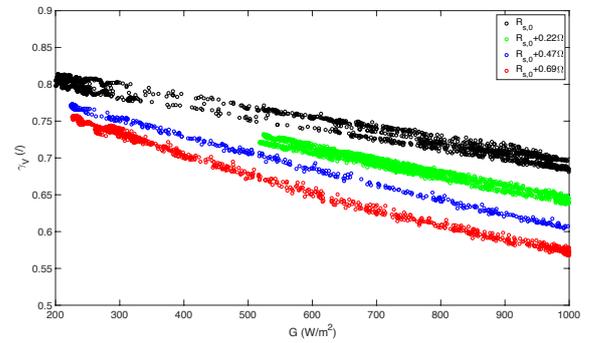


Figure 5. Identified γ_V as a function of irradiance. $R_{s,0}$ is the series resistance of the PV module without any additional resistor.

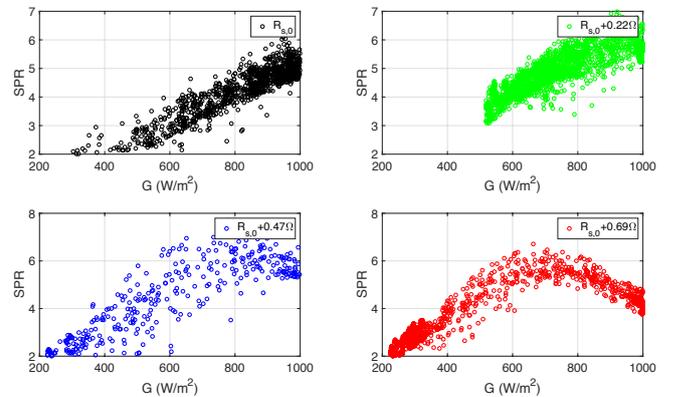


Figure 6. Identified SPR values as function of irradiance for different series resistances.

It is worth to note that the proposed procedure allows diagnosing series resistance degradation using the SPR without measuring the irradiance and temperature at which the module is operating. Indeed, in the proposed approach, such information comes from the parametric identification procedure.

IV. CONCLUSIONS

In this digest an approach to the on-line diagnosis of a PV module condition is presented via parametric identification using the single diode model. In particular, the use of the *SPR* index is presented. The experimental results show that this index allows to recognize changes in the series resistance of the PV module.

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