

# Identification and Diagnostic of a Photovoltaic Module based on Outdoor Measurements

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**Abstract**—Photovoltaic modules may be subject to significant ageing during their lifetime. This is evident especially through the value of the series resistance, which is one of the five parameters appearing in the single diode model of the module. The identification of such a value on the basis of on-field measurements is not trivial, because of the measurement noise and limitations in reaching the open circuit voltage conditions. In this paper, an approach to the identification of the operating parameters of the module through outdoor measurements is proposed. The method shows interesting features in view of its application to the detection of ageing phenomena affecting the module during its lifetime.

**Index Terms**—diagnosis, parametric identification, photovoltaic systems.

## I. INTRODUCTION

Photovoltaic (PV) modules are subject to degradation of performance during their lifetime. This can be due to accidents, e.g. heavy objects hitting the surface, or by gradual or even accelerated ageing by some events. Uneven loss of transparency of the module's frontal cover, humidity, differences of potentials among the cells, the ground and the module's envelope, and local temperature increase are only some of the causes of the reduction of the power produced by the PV module. Early detection of the performance degradation is a key factor for avoiding too large losses of the power production before performing a maintenance action or replacing the module. In literature, the number of papers dedicated to this issue is rapidly increasing. Some approaches are based on the use of thermography, but they require expensive cameras and also drones [1]–[3]. A big effort is instead oriented to having enough diagnostic information with the minimum number of sensors. Indeed, as it is known, irradiance and cell temperature sensors are generally expensive and provide only local measurements, so that their adoption, especially on PV module level, is very discouraged. Instead, as in [4], a more suitable approach is based on indicators that allow comparing some key elements of the PV module working in outdoor conditions with their reference values. The comparison is usually done by using the Maximum Power Point (MPP) voltage and current coordinates, i.e.  $V_{MPP}$  and  $I_{MPP}$ , as well as  $V_{sc}$  and  $I_{oc}$  in short and open circuit conditions, respectively. Some approaches

include also the partial shadowing as an event to detect the defined indicators. This is stated in [4] as well as in [5]: the latter one presents an approach that adopts some indicators for detecting the partial shadowing, Potential Induced Degradation (PID) and increase of the PV module internal losses. The latter ones are mainly related to the series resistance  $R_s$  of the PV module, which also appears in the Single Diode Model (SDM) shown in Fig. 1. In this model, five unknown parameters appear  $\{I_{ph}, I_s, \eta, R_s, R_{sh}\}$ , thus the photo induced current, the saturation current, the ideality factor, the series and the shunt resistances, respectively.

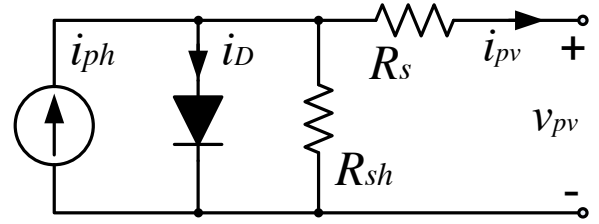


Figure 1. Single diode model of the PV module.

Some approaches identify the  $R_s$  value, as well as the values of the other four parameters appearing in the SDM, in Standard Test Conditions (STC), where the operating irradiance and temperature values are known. Instead, in outdoor conditions, the series resistance is often estimated by measuring the slope of the PV module current as a function of voltage ( $I$ - $V$ ) curve close to the open circuit conditions. Nevertheless, this approach might suffer from measurement noise and inaccuracies. Moreover, the methods that are designed for being used in STC cannot be applied in outdoor conditions, unless the operating values of irradiance  $G$  and temperature  $T$  are provided [6].

In this paper an identification procedure operating on outdoor PV module measurements is proposed. It takes as input the module's  $I$ - $V$  curve, or a portion of it across the MPP, and gives the identified values of the operating conditions, thus  $G$  and  $T$ , and of the series and shunt resistances appearing in the SDM. A number of tests performed on experimental data, which have been acquired on the PV platform installed at Tampere University, allows to

validate the procedure and show the usefulness of the results for diagnostic purposes.

The manuscript is organized as follows. Section II summarizes the numerical procedure adopted for parametric identification. Section III shows the results achieved in a number of experimental cases. Conclusions end the paper.

## II. THE IDENTIFICATION PROCEDURE

The identification procedure is based on the use of the built-in Matlab function *fit.m*. It implements a non linear minimization of an objective function through the well known Trust Region algorithm. It needs a guess solution and also a range for each of the parameters to identify, so that the search space is bounded. The procedure identifies the set of parameters  $\{G, T, R_s, R_{sh}\}$  by minimizing the Root Mean Square Error (RMSE) between the  $I$ - $V$  curve obtained through the SDM and the one measured when the PV module works in outdoor conditions. In the next sub-sections, the steps the procedure consists of are described in sequence.

### A. Computation of the guess solution

The guess solution is calculated by referring to the data-sheet values provided by the module manufacturer. The procedure proposed in [6] (Section 2.2.2), which is based on the use of explicit equations only, is used. Its adoption ensures a low computation effort so that it can be implemented even in an embedded system.

### B. Setting of the guess solution and of the search space

The values in STC are used for starting the identification procedure of the SDM when the module works outdoors. The actual irradiance  $G$  and cell temperature  $T$  are not known, so that the parametric identification cannot be performed through the same procedure recalled in the previous sub-section and referred to the STC. Thus, the extended set of parameters  $\{G, T, I_{ph}, I_s, \eta, R_s, R_{sh}\}$  should have to be identified. Nevertheless, two main dependences from  $G$  and  $T$  can be evidenced; they concern the photo-induced current  $I_{ph}$  and the saturation current  $I_s$  as it follows:

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

$$I_s = C_{STC} T^3 e^{-\frac{E_g(T)}{kT}}, \quad (2)$$

where  $\alpha_I$  is the thermal coefficient of the panel short circuit current,  $C_{STC}$  is a coefficient calculated at STC and all the quantities having the subscript STC are referred to the Standard Test Conditions [6].  $E_g(T)$  is the material band gap at the temperature  $T$ , which is determined as [6]:

$$E_g(T) = E_{g,STC} [1 + \alpha_E \cdot (T - T_{STC})], \quad (3)$$

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

A further dependency on the cell temperature appears in the thermal voltage of the cell:

$$a = \frac{N_s \eta k T}{q}, \quad (4)$$

where  $N_s$  is the number of series connected cells of the module,  $k$  is the Boltzmann constant and  $q$  the electron charge. Parameter  $a$  has to be taken into account when the PV module current is explicitly calculated as a function of the voltage through the Lambert W-function [6]:

$$I = \frac{R_{sh}(I_{ph} + I_s) - V}{R_s + R_{sh}} - \frac{a}{R_s} W(\theta) \quad (5)$$

wherein:

$$\theta = \frac{R_s R_{sh} I_s}{a(R_s + R_{sh})} e^{\frac{R_s R_{sh}(I_{ph} + I_s) + R_{sh} V}{a(R_s + R_{sh})}} \quad (6)$$

Finally, the set of parameters to be identified can be limited to  $\{G, T, \eta, R_s, R_{sh}\}$ . Furthermore, also the parameter  $\eta$  can be kept fixed at its STC value, by considering its weak dependency on the irradiance and temperature conditions [7]. As a consequence, the set of identified parameters has been finally fixed to  $\{G, T, R_s, R_{sh}\}$  in this paper.

### C. Identification procedure

It is assumed that the  $I$ - $V$  curve of the PV module is acquired while it is working in outdoor conditions. The RMSE between the experimentally acquired samples and the samples generated through (5) for a given set of parameters has to be minimized. Any identified set of  $\{G, T, R_s, R_{sh}\}$  allows to calculate  $I_{ph}$  and  $I_s$  through (1), (2) and (3), then (4) and (6) are used to compute  $a$  and  $\theta$  so that the samples of the PV module current  $I$  can be calculated for any sample  $V$  of the PV module voltage. Thus, the best set of  $\{G, T, R_s, R_{sh}\}$  that minimizes the RMSE can be determined through a minimization approach.

## III. EXPERIMENTAL RESULTS

The experimental results are based on  $I$ - $V$  curves measurements acquired at the PV research 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. Its STC electrical performance is summarized in Table I.

TABLE I. ELECTRICAL PARAMETERS OF THE NAPS NP190GKG PANEL IN STC.

Parameter	Value
$I_{sc}$	8.00 A
$I_{MPP}$	7.36 A
$V_{oc}$	33.0 V
$V_{MPP}$	25.8 V
$\alpha_I$	0.0047 A/K
$\alpha_V$	-0.124 V/K

The procedure recalled in Section II.A gives the identified values of the five parameters of the SDM that are reported in Tab. II. As stated in Section II, these values are considered as the guess solution of the fitting procedure in STC presented in this paper.

TABLE II. SDM PARAMETERS FOR THE NAPS NP190GKG PANEL IN STC.

Parameter	SDM parameters in STC
$I_{ph,STC}$	8.00 A
$I_{s,STC}$	1.6993 nA
$\eta_{STC}$	1.0686
$R_{s,STC}$	0.3786 $\Omega$
$R_{sh,STC}$	122.56 $\Omega$

The guess solution and the ranges of the identified parameters are listed in Tab. III. They are required by the fitting procedure used in this paper for measured  $I$ - $V$  curves.

TABLE III. GUESS SOLUTION AND SEARCH SPACE OF THE PARAMETERS.

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

Two curves, acquired at different irradiance and temperature values, have been used for testing the effectiveness of the approach. The experimental points and the fitted curves are shown in Fig. 2 and Fig. 3. The good quality of the fitting is evident in the figures, which is obtained by the sets of parameters listed in Tab. IV. Fig. 3 allows to put into evidence the significant noise affecting the experimental points in proximity of the open circuit voltage, which is naturally smoothed by the fitting operation.

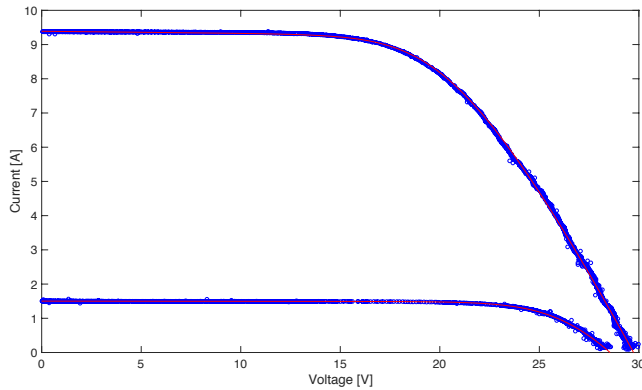


Figure 2. Experimental points (blue markers) and fitted curves (in red color).

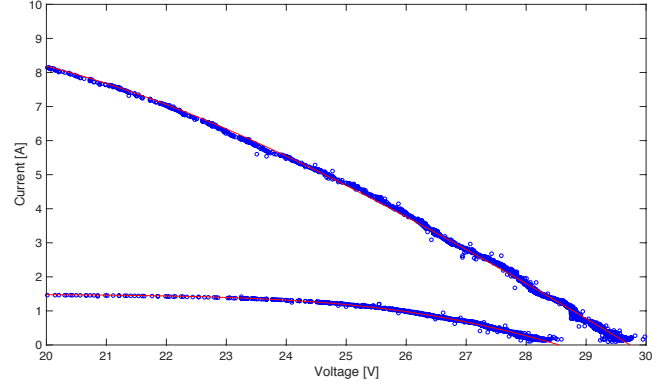


Figure 3. Detail of the results shown in Fig. 2 in proximity of the open circuit voltage.

TABLE IV. IDENTIFIED PARAMETER VALUES AT LOW AND HIGH IRRADIANCE LEVELS.

Parameter	Curve at low G	Curve at high G
$G$ [ $W/m^2$ ]	186.4	1162
$T$ [ $^{\circ}C$ ]	37.9	49.5
$R_s$ [ $\Omega$ ]	0.9294	0.7706
$R_{sh}$ [ $\Omega$ ]	1834	168

The identified values of  $G$  and  $T$  given in Tab. IV are compared with the experimental measurements obtained through a pyranometer and a temperature sensor placed on the back side of the module. As for the curve at low irradiance,  $G_{measured} = 154 W/m^2$  and  $T_{measured} = 35.2 ^{\circ}C$ , thus the fitting has 17% and 7% overestimations, respectively. At high irradiance, instead,  $G_{measured} = 1056 W/m^2$  and  $T_{measured} = 46.2 ^{\circ}C$ , resulting in 9% and 7% overestimations, respectively. The overestimation of the irradiance level is due to an underestimation of the short circuit current in STC given by the manufacturer in the data sheet. This has been confirmed by many measurements performed at Tampere University. The 7% overestimation in terms of temperature is reasonable because the measured temperature is at the module back side while the estimated temperature is referred to the cells temperature. Moreover, inhomogeneity of the temperature distribution can occur in practice, but this cannot be caught by the model, because it assumes that all the cells in the module work at the same temperature. Furthermore, it has to be noticed that two cables of 53.5 m length and having a total equivalent resistance of 0.363  $\Omega$  are connected to the module's terminals and used for acquiring the  $I$ - $V$  curves in the laboratory. Thus, at high irradiance, the cable resistance has to be subtracted from  $R_s = 0.7707 \Omega$ , so that a resistance of 0.4076  $\Omega$  is obtained for the module, which is almost equal to the value obtained in STC and shown in Tab. II.

In order to validate the ability of the proposed approach in identifying the actual value of the series resistance of the module, an experiment has been conducted on the same PV module analyzed before. The  $I$ - $V$  curve has been repeatedly acquired in sunny days in four different conditions, namely by adding, in sequence, three resistors in series having different

resistances. The first one is of  $0.22 \Omega$ , the second one of  $0.47 \Omega$  and the third one of  $0.69 \Omega$ . The result is shown in Fig. 4. The curves giving identified values of  $G$  in the range  $[900, 1000] \text{ W/m}^2$  have been isolated and the values of the identified corresponding series resistances have been plotted with different colors, depending on the value of the series resistance added to the PV module. It is worth noting that the distributions of dots for the different colors are different, because the measurements were done in different sunny days with different additional resistances for the same PV module. Fig. 4 shows that the proposed algorithm allows to identify a stable value of the series resistance for each set of measurements. The black dots in the figure, which have been obtained without any additional resistance, are coherent with that one for  $R_s$  shown in the third row of Tab. IV. The distributions of the dots are almost horizontal meaning that, in that range of  $G$ , the identified  $R_s$  value is very stable. This allows discriminating one resistance value from another one very well. Fig. 5 confirms this result also if the identification is done at a medium value of the irradiance, thus in the range of  $G$  equal to  $[500, 600] \text{ W/m}^2$ .

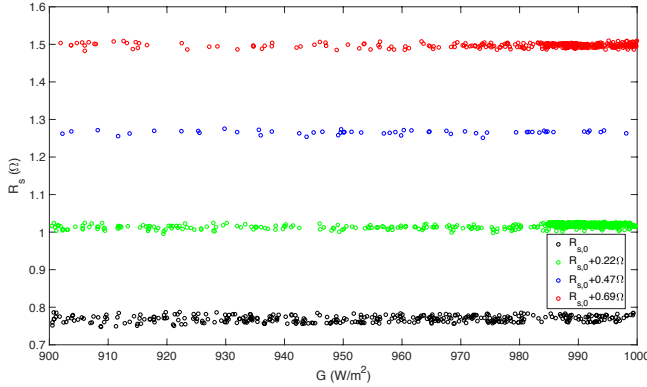


Figure 4. Identified series resistances at high irradiance.  $R_{s,0}$  is the series resistance of the PV module without any additional resistor.

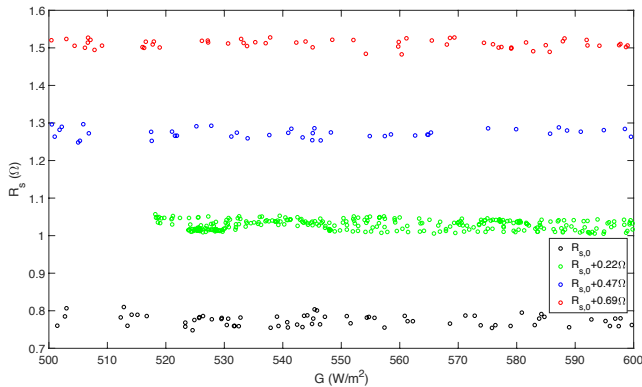


Figure 5. Identified series resistances at medium irradiance.  $R_{s,0}$  is the series resistance of the PV module without any additional resistor.

## IV. CONCLUSIONS

In this paper an approach is presented for the parametric identification of the SDM of a PV module. The method operates on the module's  $I$ - $V$  curve acquired during outdoor operation and it is able to identify the actual value of the operating irradiance and cell temperature, as well as the series and the shunt resistances appearing in the SDM. The computation complexity of the adopted model and the accuracy of the results seem to ensure a good compromise for the porting of the approach to an embedded system for on-site operation. The results achieved in terms of identification of the series resistance are promising in view of the application of the method for PV module diagnostic purposes.

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