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A novel technique for online monitoring of photovoltaic devices degradation

Antonio Faba[a], Stefano Gaiotto[b], Gabriele Maria Lozito[b,*]

[a] Department of Engineering, University of Perugia, Perugia, Italy
[b] Department of Engineering, Roma Tre University, Rome, Italy

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ABSTRACT

A novel methodology to assess the degradation of a photovoltaic module is presented. The degradation of the module can be represented by a progressive alteration of the equivalent One-Diode circuit model for the device. The involved circuit elements are the series and shunt resistances. It is possible to estimate the alterations for these elements by measuring the divergence between the model and the device behaviour. Two novelties are the key aspects of this work. First, the model is identified through a very accurate procedure. Second, the irradiance is estimated directly by means of the photovoltaic device, without need for additional sensors. The result is a completely on-line estimation of the module degradation that does not require any change in the operating point.

1. Introduction

Solar energy harvesting requires initial remarkable investments that must be carefully evaluated, considering the revenues that are expected to return in the following years Kato et al. (1998). Usually PV panels manufactures guarantee their products for about 25 years. Indeed, the return of investment must happen during the solar panels expected life. Unfortunately, it has been observed that some panels suffer from early degradation due to the outdoor operation Munoz et al. (2011), Bastidas-Rodriguez et al. (2017), Accarino et al. (2013), Desoto et al. (2006). This degradation reduces notably the available power Kaplanis and Kaplani (2011) as can be observed if a characterization of the PV panel is performed after degradation took place Osterwald (2003), Gaiotto et al. (2015). It is possible to model the PV by means of the One-Diode model, that is a very common circuit model found in literature. Through this modelling, the process of degradation can be represented by a progressive increment of the series resistance and a progressive reduction of the shunt resistance. This means that a model identified from datasheet values Laudani et al. (2014b, 2013) or by experimental curves Laudani et al. (2014a) will lose accuracy over time. An accurately identified model is critical for several applications, among which Maximum Power Point Tracking Vincheh et al. (2014), Mahamad and Saon (2014), Lei et al. (2011), Kazmi et al. (2009) (especially for Neural Network based approaches Laudani et al. (2014d), Lozito et al. (2014)) and solar irradiance measurement Oliveri et al. (2017), Carrasco et al. (2017), Mancilla-David et al. (2014). Constant monitoring of the process of degradation is a difficult issue (an interesting review on photovoltaic degradation rate methodologies can be found in Phinikarides et al. (2014)). Possible solutions revolving around maintenance and fault assessment relies on soft computing techniques such as Neural Networks (NN) Chine et al. (2016), Li et al. (2012). Other procedures make use of a comparison between the panel expected behaviour (i.e. the model's, not taking into account degradation) and the measured one (i.e. the one influenced by degradation). An example of this procedure can be found in Bastidas-Rodriguez et al. (2017), and it constitutes the starting point of this work. With respect to Bastidas-Rodriguez et al. (2017), this work introduces two major advantages. First, the model identification is performed with an advanced technique able to reduce the number of parameters from 5 to 2 Laudani et al. (2014b). This yields a better accuracy and a simpler procedure for model identification. Second, since the algorithm for degradation estimation in Bastidas-Rodriguez et al. (2017) requires knowing the environmental quantities of temperature (T) and irradiance (G) for correct model computation, an analytic expression to compute G from actual temperature and workpoint (v,i) is proposed. The approach is tested twofold. First, the increased accuracy obtained by identification thorough Laudani et al. (2014b) is validated by identifying the PV device Kyocera KC200GT (rated 200 W) from datasheet values and then testing the accuracy of the model against experimental data at different G,T conditions. Second, the irradiance analytic expression is used to monitor a simulated degradation of the panel BP 3235T (rated 235 W).

The paper is structured as follows. In the second section, the five parameters model and the degradation indicators proposed by Bastidas-Rodriguez et al. (2017) are presented. In the third section, the proposed improvements for the procedure are discussed. In the fourth section, the results for panel identification and degradation monitoring are

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* Corresponding author.
E-mail address: gabrielemaria.lozito@uniroma3.it (G.M. Lozito).

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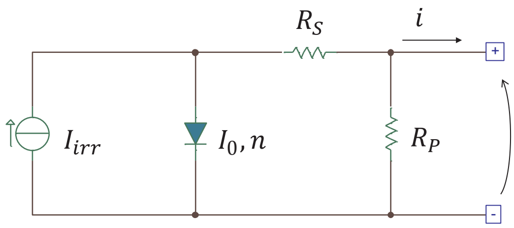

Fig. 1. One-diode equivalent circuit for a single PV solar cell.

presented, along with computational costs analysis and application possibilities. Conclusions and final remarks close the paper.

2. A model for a PV device and its degradation over time

A very common circuit model used in literature to represent the behaviour of a PV device is the one-diode model, which is shown in Fig. 1. The model was originally conceived to represent a single PV cell, however, by a proportional modification of the parameters, it can represent a panel composed by N_S cells in series, and N_P strings in parallel. The characteristic of this circuit model is given in Eq. (1).

$$i = I_{\mathrm{irr}} - I_0\left[\exp\left(\frac{q(v+iR_{\mathrm{S}})}{N_{\mathrm{S}}nkT}\right)-1\right]-\frac{v+iR_{\mathrm{S}}}{R_{\mathrm{SH}}} \tag{1}$$

where $q = 1.602 \times 10^{-19}$ C is the electron's electric charge, $k = 1.3806503 \times 10^{-23}$ J/K is the Boltzmann constant, and n is the ideality factor, I_{irr} is the photo current (or irradiance current) generated when the cell is exposed to sunlight; I_0 is the diode saturation current (or cell reverse saturation current). Eq. (1) is an implicit non-linear equation that must be solved numerically. Although no analytic solution exist for this equation, it is possible to formulate an alternative explicit relation expressing the voltage as a function of the current via Lambert W function. The model is characterized by five parameters that define the circuit elements of Fig. 1. The five parameters are the independent generator current I_{irr}, the inverse saturation current for the diode I_0, the ideality factor for the diode n, the series resistance R_S and the shunt resistance R_{SH}. Those five parameters depend (see De Soto et al. (2006)) on the environmental conditions G, T, and their reference values measured at standard reference condition (SRC, $T_{ref} = 25$ °C, $G_{ref} = 1000$ W/m^2), namely $G_{\mathrm{ref}}, T_{\mathrm{ref}}, I_{\mathrm{irr,ref}}, I_{0,\mathrm{ref}}, R_{\mathrm{SH,ref}}, R_{\mathrm{S,ref}}$, and n_{ref}, as described by Eq. (2) through Eq. (6),

$$I_{\mathrm{irr}} = \frac{G}{G_{\mathrm{ref}}}(I_{\mathrm{irr,ref}} + \alpha_{\mathrm{T}}(T - T_{\mathrm{ref}})) \tag{2}$$

$$I_0 = I_{0,\mathrm{ref}}\left(\frac{T}{T_{\mathrm{ref}}}\right)^3 \exp\left(\frac{E_{\mathrm{g,ref}}}{kT_{\mathrm{ref}}} - \frac{E_{\mathrm{g}}}{kT}\right) \tag{3}$$

$$R_{\mathrm{SH}} = R_{\mathrm{SH,ref}}\left(\frac{G_{\mathrm{ref}}}{G}\right) \tag{4}$$

$$R_{\mathrm{S}} = R_{\mathrm{S,ref}} \tag{5}$$

$$n = n_{\mathrm{ref}} \tag{6}$$

In Eq. (2) α_T is the temperature coefficient of the short–circuit current which represents the rate of change of the short–circuit current with respect to T. In Eq. (3), E_{g} is the bandgap energy for silicon in eV expressed by:

$$E_{\mathrm{g}} = 1.17 - 4.73 \times 10^{-4} \times \frac{T^2}{T+636}. \tag{7}$$

Identification of this model is an open problem in literature. Producers of PV devices usually report in their datasheet the following data, valid at SRC:

- V_{OC}: The open circuit voltage
- I_{SC}: The short circuit current
- V_{mpp}: The voltage at maximum power point
- I_{mpp}: The current at maximum power point
- $\alpha_{V_{OC}}$: Temperature Coefficient of V_{OC}
- $\alpha_{I_{SC}}$: Temperature Coefficient of I_{SC}

Starting form these parameters, in Bastidas-Rodriguez et al. (2017) and Accarino et al. (2013) a procedure is proposed to identify the one-diode model by means of the following equations:

$$I_{irr} \approx I_{SC} \tag{8}$$

$$n = \frac{\alpha_{V_{OC}} - V_{OC}/T}{N_s V_t\left(\frac{\alpha_{I_{SC}}}{I_{irr}} - \frac{3}{T} - \frac{E_{gap}}{kT^2}\right)} \tag{9}$$

$$I_0 \approx I_{irr} e^{-\frac{V_{OC}}{N_s n V_t}} \tag{10}$$

$$\theta = \frac{V_{mpp}(2I_{mpp} - I_{irr})\exp\left(\frac{V_{mpp}(V_{mpp} - 2N_s n V_t)}{N_S n^2 V_t^2}\right)}{N_s n I_0 V_t} \tag{11}$$

$$x = W(\theta) + 2\frac{V_{mpp}}{N_S n V_t} - \frac{V_{mpp}^2}{N_S n^2 V_t^2} \tag{12}$$

$$R_S = \frac{x N_S n V_t - V_{mpp}}{I_{mpp}} \tag{13}$$

$$R_{SH} = \frac{x N_S n V_t}{I_{irr} - I_{mpp} - I_0(e^x - 1)} \tag{14}$$

where $W(\theta)$ is the Lambert Function of argument θ. During PV panel lifetime, due to outdoor operations, panel performance may change. In particular, it is possible to observe a reduction in V_{mpp} and I_{mpp}. In terms of the One-Diode model, it corresponds to a reduction in R_{SH} and an increase in R_S. In Bastidas-Rodriguez et al. (2017) it is proposed to evaluate this degradation online (i.e. in operative condition), by using the following expressions:

$$\Delta R_S = \frac{v(I_{mpp}) - V_{mpp}}{I_{mpp}} \tag{15}$$

and

$$\Delta R_{SH} = \frac{V_{mpp}}{i(V_{mpp}) - I_{mpp}} \tag{16}$$

The two indicators proposed express the degradation as a discrepancy between the actual (degraded) panel performance and the model behaviour (uninfluenced by the degradation). The former is expressed by the values of V_{mpp} and I_{mpp}. Those values are measured experimentally with a rather good precision if a good MPPT controller is implemented in the PV system. The latter are the values of $v(I_{mpp})$ and $i(V_{mpp})$. Those values are the MPP coordinates on the I-V curve given by Eq. (1) (thus, the ones from the undegraded model). Concerning the solution of Eq. (1), it is possible to do it numerically by using a simple SW routine employing, for example, the Newton's method, or by means the Lambert W function. In Bastidas-Rodriguez et al. (2017) it is proven that Eqs. (15) and (16) provide a good estimation of Eqs. (13) and (14) and that they have low sensitivity with respect to irradiance and temperature. When deriving $v(I_{mpp})$ and $i(V_{mpp})$ from Eq. (1) however, the effect of both temperature and irradiance on the panel parameters must be taken into account. It is possible to accomplish this task thorough Eqs. (8)–(14). In Bastidas-Rodriguez et al. (2017) it is underlined that