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Original scientific paper

ALGORITHM TO EXTRACT MODEL PARAMETERS OF PARTIALLY SHADED PHOTOVOLTAIC MODULES

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Abstract. *Uneven irradiation, due to partial shading, can produce hot spots in photovoltaic modules. A classical solution to avoid hot spot consists in using bypass diodes in antiparallel to series-connected cell groups. This solution brings a new problem: the presence of multiple local maximum power points. We present a simple algorithm for fast extraction of the model parameters of partially shaded photovoltaic panels with bypass diodes. An example of the application of the proposed algorithm is illustrated using the data from a real monocrystalline silicon technology photovoltaic module measured under uniform illumination and partial shading conditions. The possibility of using the algorithm as a practical approximate solution is also discussed. The simulations, using only four parameters, represent reasonably well the measured data.*

Key words: *Maximum Power Point (MPP), Partial shading, Photovoltaic module, Solar cell.*

1. INTRODUCTION

Photovoltaic (PV) arrays frequently consist of strings of series-connected PV cells that are connected in parallel to achieve given power requirements [1-3]. PV panels made up of such arrays can be seriously affected by partial shading conditions which occur when clouds, buildings, trees, dirt or any other opaque body partially obstruct the radiation falling on the panel. In a series connection configuration, partial shading conditions can cause shaded cells to become reverse biased and start to generate heat instead of producing energy. In order to avoid this situation, bypass diodes are customarily connected in antiparallel to series-connected cell groups. This use of such bypass diodes causes the emergence of multiple local maximum power points that complicate deciding where the global maximum is. Several PV array reconfiguration techniques have been proposed to mitigate partial shading effects. An outstanding review article on the topic was authored by Belhachat and Larbes in 2021 [4].

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Parameter extraction of uniformly illuminated solar cells (SCs) and photovoltaic (PV) cell arrays' models is an important subject of continuous interest to device designers and PV systems engineers [5-11]. At the same time, partial shading (PS) of solar cell arrays is a frequent occurrence in actual outdoors operation. Because of its grave consequences on overall PV system performance deterioration, this topic has been and continues to be the subject of serious concern and intense study [12-15].

It is important to understand the effect of partial shading in order to improve the performance of the solar panels. In 2020, Kermadi et al. presented a general analytic approach to study partial shading effects based on modeling each component of the panel and then obtaining the total current-voltage characteristic for each region of operation [16]. In the last three years, many articles have been dedicated to partial shading effects [12-19]. For example, in [3,17,18], different array configurations have been evaluated under partial shading conditions. In particular, dynamic array reconfiguration seems to be a good solution to disperse the partial shading over the entire array and hence mitigate the partial shading effects [17,18]. On the other hand, bifacial photovoltaic modules have also been studied under partial shading conditions [19].

In this article we present a simple algorithm to extract the model parameters of partially shaded photovoltaic modules with bypass diodes to reduce the possible occurrence of hot spots in shaded cells. The proposed procedure is based on an effective array model that mimics the well-known five parameter Single Diode (SD) solar cell model. The effective model's parameters are described through analytical equations expressed in terms of the PV module's short circuit current I_{sc}, open circuit voltage V_{oc}, and the voltage and current coordinates (V_{mppx}, I_{mppx}) of whatever multiple Maximum Power Points (MPPs) happen to appear on the measured I-V characteristics.

This article is organized as follows. Section 2 presents the model equation for a uniformly illuminated array connected in series-parallel. Section 3 illustrates measurements of a partially shaded module having two maxima power points. Section 4 presents a simple model for partial shading conditions. Finally, section 5 contains the conclusions.

2. Model Equation for a Uniformly Illuminated Array

The *I-V* characteristics of any illuminated solar cell may be most simply represented by the SD model and its corresponding lumped-element equivalent circuit [5-11]. This circuit, shown in Fig. 1, consists of a single exponential-type non-ideal diode defined by its two parameters, the reverse saturation current I_0, and the ideality factor n, a photo-generated constant current source of intensity I_{ph} dependent on the illumination level, and possibly including two types of parasitic linear losses, a junction shunting parallel conductance of constant magnitude G_p and a resistance in series with the terminals of constant magnitude R_s.

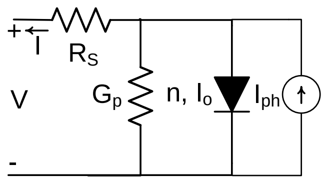

Fig. 1 Single diode lumped-element equivalent circuit model with parasitic parallel and series resistive losses valid for solar cells and photovoltaic arrays

The mathematical description of this lumped element equivalent circuit model is given by the following implicit equation:

$$I = -I_0 \left[exp\left(\frac{V+IR_s}{nV_{th}}\right)\right] - (V + IR_s)G_p + I_{ph} \tag{1}$$

where I is the terminal current, V is the terminal voltage, and $V_{th} = k_B T/q$ is the thermal voltage. By using the Lambert W function, the previous implicit equation was first solved, for the particular case of I_{ph}=0, by Banwell and Jayakumar in 2000 [20]; and also, by Ortiz-Conde [21]; and the general case by Jain and Kapoor in 2004 [22]. Approximate solutions of multi-exponential solar cell models, using the Lambert W function, were presented in 2012 [23].

Consider now a PV array composed of a certain number N_p of parallel connected solar cell strings, where each of the strings contains a number N_s of series connected solar cells, as illustrated in Fig. 2. Assuming that all the cells are identical and uniformly illuminated, the current at the array's terminals may be described by a lumped-element equivalent circuit model for a single solar cell, like the one shown in Fig. 1. Likewise, its corresponding equation is similar to (1) for a single solar cell, but instead of the five solar cell parameters (I_{ph}, n, I_o, R_s and G_p), it contains five effective parameters (I_{phef}, n_{ef}, I_{oef}, R_{sef} and G_{pef}) that describe this array as an effective solar cell. These effective parameters are defined in terms of the single cell parameters and the total number of cells connected in series N_s and cell strings in parallel N_p, as follows:

$$\begin{gathered} I_{phef} = N_p I_{ph}, \quad n_{ef} = N_s n, \quad I_{oef} = N_p I_o \\ R_{sef} = \frac{N_s}{N_p} R_s, \quad G_{pef} = \frac{N_p}{N_s} G_p \end{gathered} \tag{2}$$

We wish to point out here that the above mentioned effective model and parameter definitions can be readily demonstrated; and that effective SD model equations of this type are routinely used without overtly referring to their parameters as "effective" [24-26]. Here, although we will be talking about array models, for the sake of conciseness, from now onward we will drop the "ef" subscript when writing the effective parameters' names, keeping in mind that their true meaning is defined in (2).

3. Example of a Partially Shaded Module

Experimental data of a mono-crystalline silicon technology PV module with bypass diodes, measured at constant ambient temperature and under various natural terrestrial sunlight illumination conditions, was obtained from the US National Renewable Energy Laboratory (NREL). Figure 3 presents six *I-V* characteristics of this module measured at six instants during the time span from 7:00 to 10:00am on 24 April 2013, in the city of Golden, Colorado, U.S.A. [27]. More than 180 non-uniformly spaced data points were recorded at the module's external terminals within the range from (V=0, $I=I_{sc}$) to ($V=V_{oc}$, I=0).

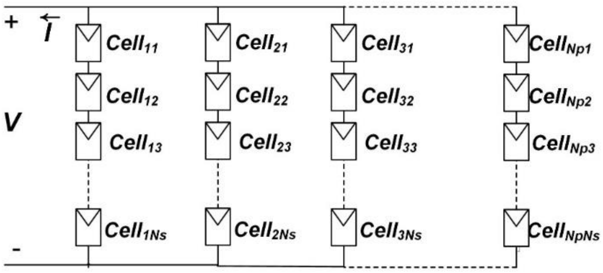

Fig. 2 A generic PV array with N_p parallel connected cell strings, where each string has N_s series connected cells

The five power (P=IV) vs voltage curves, presented in the lower pane of Fig. 3, which were calculated from their respective *I-V* characteristics data measured every half hour from 7:00am to 9:00am, exhibit two distinct maxima, whereas the one *P-V* curve, corresponding to the later 10:00am measurement, exhibits only one maximum. The presence of two power maxima is a clear indication of partial shading. It seems that during the time of the first five measurements (7:00am to 9:00am) part of the PV module was shaded, receiving much less illumination than the other part, which was fully illuminated. The change from two power maxima to the single maximum observed for the 10:00am measurement indicates that by that time the partial shading had ceased and the whole module had become fully illuminated. The hourly progression of the measured *I-V* characteristics, presented in the upper pane of Fig. 3, further confirms that this particular PV module contains two distinguishable series connected parts, and that they most likely are equal halves, each one consisting of an array of solar cells shunted by a bypass diode [28-30].

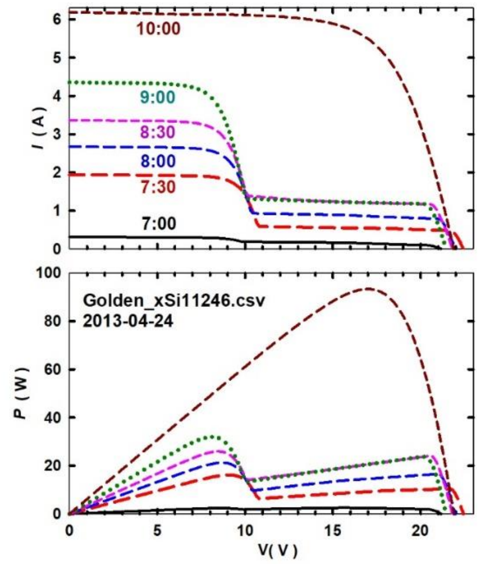

Fig. 3 NREL data of mono-crystalline silicon technology PV module, measured on April 24, 2013 at various times in Golden, Colorado, USA [24]

To analyze the *I-V* and *P-V* characteristics shown in Fig. 3, we will first examine the curves that correspond to the data measured at 10:00am, which is the time when the whole PV module was uniformly illuminated and both bypass diodes were in the off state. For convenience we will assume that the module has negligible parasitic losses, i.e. R_s =0 and G_p=0. In such case we may use a simplified approximate effective solar cell SD model to describe the whole module using just 3 effective parameters [31-32]: I_{ph}, n, and I_0. Thus, (1) reduces to:

$$I = I_{ph} - I_0 \left[exp\left(\frac{V}{nV_{th}}\right) - 1 \right] \tag{3}$$

Next, we will find the values of these three effective model parameters I_{ph}, n, and I_0 by extracting them from the known coordinates of the three most prominent points in a PV module's *I-V* characteristics: the short circuit current I_{sc}, the open circuit voltage V_{oc} and the MPP (V_{mpp}, I_{mpp}), as measured in this case at 10:00am under uniform illumination.

Evaluation of (3) at the short circuit condition (V=0, I=I_{sc}) tells us that in this ideal case with R_s≈0 and G_p≈0. the effective photo-generated current is equal to the measured short circuit current: $I_{ph} = I_{sc}$. Please be reminded that this is the "effective" photo-current generated by the whole module, and that according to (2), it is equal to the photo-current generated by a single cell multiplied by the module's total number of cell strings connected in parallel N_p.

The derivative of the current through the PV module's terminals with respect to the voltage across them gives the slope at any point on the *I-V* characteristics, and is obtained by differentiating (3):

$$\frac{dI}{dV} = \frac{-I_0}{nV_{th}} exp\left(\frac{V}{nV_{th}}\right) \tag{4}$$

To be able to achieve maximum output power any photovoltaic cell, array or module must be presented with an optimal load that allows it to operate at its MPP. In this sense, the MPP may be defined as the point (V_{mpp}, I_{mpp}) on the *I-V* characteristics where the curve's slope and the ratio of its two coordinates I_{mpp}/V_{mpp} become equal in magnitude but opposite in sign [33], i.e.:

$$-\frac{I_{mpp}}{V_{mpp}} = \left.\frac{dI}{dV}\right|_{MPP} = \frac{-I_0}{nV_{th}} exp\left(\frac{V_{mpp}}{nV_{th}}\right) \tag{5}$$

Evaluating (3) at the MPP, ignoring the -1 term, recalling that $I_{ph} = I_{sc}$, substituting it into (5) and solving for the effective ideality factor n yields:

$$n \approx \frac{(I_{sc} - I_{mpp})V_{mpp}}{V_{th} I_{mpp}} \tag{6}$$

Finally, the effective I_0 is calculated using (3) evaluated at the open circuit condition (V=V_{oc}, I=0), ignoring the -1 term and recalling that $I_{ph} \approx I_{sc}$:

$$I_0 \approx I_{sc} exp\left(-\frac{V_{oc}}{nV_{th}}\right) \tag{7}$$

Figure 4 presents the module's data under uniform illumination, measured at 10:00 am, together with the playback of the approximate SD model without series or parallel resistive losses, calculated with the three parameter values: I_{ph}=6.18A, n=81.3 and I_o=190 μA, as extracted from the coordinate values of I_{sc}=6.18A, V_{oc}=21.90V, I_{mpp}=5.50A and V_{mpp}=16.98V, using equations I_{ph}=I_{sc}, (6) and (7). The thermal voltage was taken to be 0.0259V. This simple approximate SD model with just 3 parameters appears to be good enough to simulate, within a reasonably small error, a close description of the module's *I-V* characteristics under uniform illumination, as can be seen in Fig. 4.

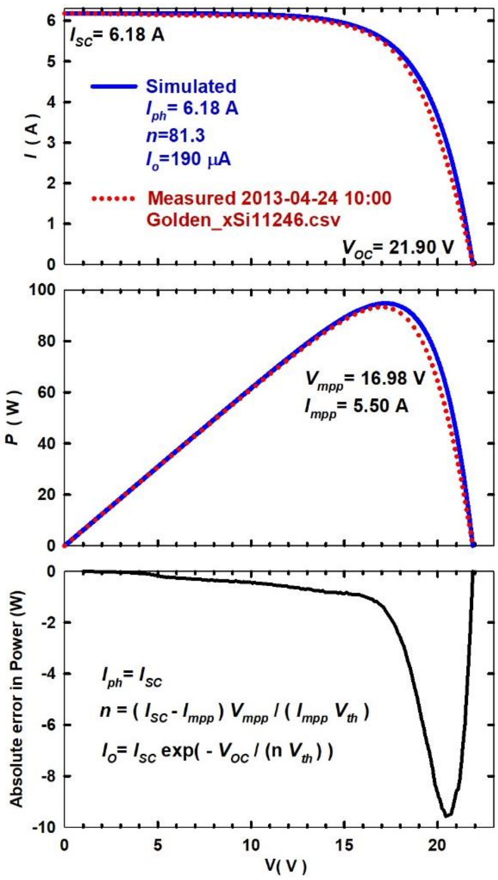

Fig. 4 Module's measurements at 10:00 am under uniform illumination and the SD model simulation using only 3 extracted parameters: I_{ph}=6.18A, n=81.3 and I_o=190 μA

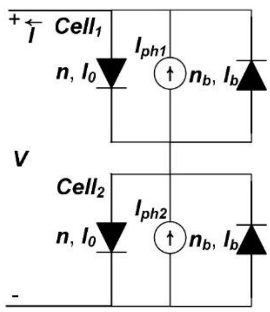

Fig. 5 Proposed lumped-element equivalent circuit model of the studied PV module, where its two parts (arrays) are represented by two ideal SD "effective cells," each one shunted by a bypass diode

4. Modeling under Partial Shading

The *I-V* characteristics with two power maxima (two MPPs), shown in Fig. 3 suggest the use of the model presented in Fig. 5, in which two arrays are represented by two "effective cells," with 4 effective parameters n, I_o, I_{ph1} and I_{ph2}, and two bypass diodes with parameters n_b and I_b.

In order to extract the 4 effective parameters, n, I_o, I_{ph1} and I_{ph2}, we will only use I_{sc}, V_{oc}, and the coordinates of the MPPs: V_{mpp1}, I_{mpp1}, V_{mpp2}, and I_{mpp2}. It is assumed in this analysis that $I_{ph1} < I_{ph2}$ and that there are two regions of operation: a) $I < I_{ph1}$ where both bypass diodes are reversed biased (turned off); and b) $I_{ph1} < I < I_{ph2}$ where bypass diode across array 1 is forward biased (turned on) while the other is reversed biased (turned off).

In region of operation b) where $I_{ph1} < I < I_{ph2}$, neglecting the forward-biased voltage drop of the bypass diode, yields:

$$I_{ph2} = I_{sc} \tag{8}$$

Let us now analyze the first MPP at I_{mpp1}, which is located in region of operation a) where $I < I_{ph1}$. Within this region there will be a nearly constant voltage drop across array 2, because $I_{ph2} > I_{mpp1}$. This constant voltage (V_{ct}) may be approximated neglecting the bypass diode and using equation 3 with the values $I = I_{mpp1}$, $V = V_{ct}$ and $I_{ph} = I_{ph2}$. That is:

$$I_0 exp\left(\frac{V_{ct1}}{nV_{th}}\right) \approx I_{ph2} - I_{mpp1} \tag{9}$$

Considering the open circuit voltage (I =0) and the constant voltage V_{ct} across array 2, we can substitute I =0, V=(V_{oc}-V_{ct}) and $I_{ph} = I_{ph1}$ into (3) to obtain:

$$0 \approx I_{ph1} - I_0 exp\left(\frac{V_{oc}-V_{ct}}{nV_{th}}\right) \tag{10}$$

Now, combining (9) and (10), and solving for I_0, yields:

$$I_0 = \sqrt{I_{ph1}\left(I_{ph2} - I_{mpp1}\right) exp\left(-\frac{V_{oc}}{nV_{th}}\right)} \tag{11}$$

At $I = I_{mpp1}$ and array 2 with an approximately constant voltage V_{ct} across it, the following relationship is obtained:

$$\left.\frac{dI}{dV}\right|_{V=V_{mpp1}} = -\frac{I_{mpp1}}{V_{mpp1}} \approx -\frac{I_0}{nV_{th}} exp\left(\frac{V_{mpp1}-V_{ct}}{nV_{th}}\right) \tag{12}$$

Using (3) with $I = I_{mpp1}$, $V = V_{mpp1}$-V_{ct} and $I_{ph} = I_{ph1}$:

$$I_{mpp1} = I_{ph1} - I_0 exp\left(\frac{V_{mpp1}-V_{ct}}{nV_{th}}\right) \tag{13}$$

Combining (12) and (13), and solving for I_{ph1}:

$$I_{ph1} = I_{mpp1}\left(1 + \frac{n\,V_{th}}{V_{mpp1}}\right) \tag{14}$$

At $I = I_{mpp2}$, the bypass diode across array 1 is forward biased (turned on) so that array 1 is effectively eliminated. Then, using equation (6) with $I_{mpp} = I_{mpp2}$ and $V_{mpp} = V_{mpp2}$:

$$n \approx \frac{(I_{sc}-I_{mpp2})V_{mpp2}}{V_{th}\,I_{mpp2}} \tag{15}$$

Figure 6 shows the data measured at 9:00 am (when there was partial shading) and the AIM-SPICE model playback simulations [34], using the lumped-element equivalent circuit model shown in Fig. 5 with the four "effective cell" parameters: I_{ph2}, I_o, I_{ph1} and n, as extracted by equations (8), (11), (14) and (15), respectively. The power and the absolute error in power are also illustrated in the figure.

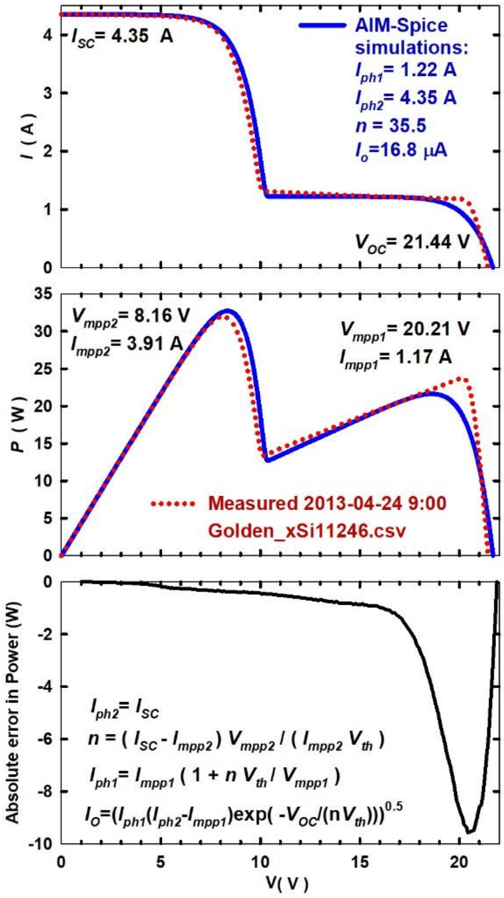

Fig. 6 Measurements at 9:00 am with two maxima power points and AIM-SPICE simulations using the 4 extracted parameters: I_{ph1}=1.22 A, I_{ph1}=4.35 A, n=35.5 and I_o=16.8 μA

5. CONCLUSION

We have presented a simple algorithm to extract the model parameters of uniformly illuminated and partially shaded photovoltaic module. The algorithm has been tested with measured data from where the model parameters where extracted. The data from the photovoltaic module used was obtained from the USA National Renewable Energy Laboratory (NREL). These NREL measurements present two maxima power points, which allows us to assume that the panel is using bypass diodes. Our simple model is based on two effective cells with two bypass diodes. Comparison between the original data and the playback of the model, as simulated using the extracted parameters, indicate that the proposed algorithm, although approximate, provides a fast and fairly accurate procedure.

The simulations represent reasonably well the measured data, considering that this model uses only four parameters, which were calculated from the known values of I_{sc}, V_{oc}, and the coordinates of the two MPPs.

We consider that the present approach could be extended to cases with 3 or more maxima power points.

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