PV panel model based on datasheet values

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***Abstract*— This work presents the construction of a model for a PV panel using the single-diode five-parameters model, based exclusively on data-sheet parameters. The model takes into account the series and parallel (shunt) resistance of the panel. The equivalent circuit and the basic equations of the PV cell/panel in Standard Test Conditions (STC)[1] are shown, as well as the parameters extraction from the data-sheet values. The temperature dependence of the cell dark saturation current is expressed with an alternative formula, which gives better correlation with the datasheet values of the power temperature dependence . Based on these equations, a PV panel model, which is able to predict the panel behavior in different temperature and irradiance conditions, is built and tested.**

I. Introduction

Nowadays the worldwide installed Photovoltaic power capacity shows a nearly exponential increase, despite of their still relatively high cost. [1] This, along with the research for lower cost and higher efficiency devices, motivates the research also in the control of PV inverters, to achieve higher efficiency and reliability. The possibility of predicting a photovoltaic plant's behavior in various irradiance, temperature and load conditions, is very important for sizing the PV plant and converter, as well as for the design of the Maximum Power Point Tracking (MPPT) and control strategy. There are numerous methods presented in the literature, for extracting the panel parameters. The majority of the methods are based on measurements of the I-V curve or other characteristic of the panel [2] [3] [4]. In this paper a photovoltaic panel model, based only on values provided by the manufacturer's data sheet, suitable for on-line temperature and irradiance estimations and model-based MPPT, is presented.

The equivalent circuit of the single-diode model for PV cells is shown below:

The general current-voltage characteristic of a PV panel based on the single exponential model is:

$$i = I_{ph} - I_o \left(e^{\frac{v+iR_s}{n_s\,V_t}} - 1 \right) - \frac{v + iR_s}{R_{sh}} \qquad (1)$$

In the above equation, V_t is the junction thermal voltage:

$$V_t = \frac{AkT_{stc}}{q} \qquad (2)$$

[1]The testing conditions to measure photovoltaic cells or modules nominal output power. Irradiance level is $1000W/m^2$, with the reference air mass 1.5 solar spectral irradiance distribution and cell or module junction temperature of 25^oC.

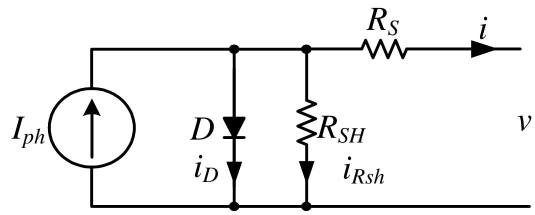

Fig. 1. Equivalent circuit of a photovoltaic cell using the single exponential model

where:

- I_{ph} - the photo-generated current in STC
- I_o - dark saturation current in STC
- R_s - panel series resistance
- R_{sh} - panel parallel (shunt)resistance
- A - diode quality (ideality) factor

are the five parameters of the model, while k is Boltzmann's constant, q is the charge of the electron, n_s is the number of cells in the panel connected in series, and $T_{stc}(^oK)$ is the temperature at STC. It is a common practice to neglect the term '-1' in (1), as in silicon devices, the dark saturation current is very small compared to the exponential term.

II. Determination of the panel model parameters from datasheet values

In order to construct a model of the PV panel, which exhibits the specifications described in the datasheet, using the above-mentioned single-diode model, there are five parameters to be determined: I_{ph}, I_o, A, R_s, and R_{sh}. The goal is to find all these parameters without any measurement, using only the data from the product data-sheet.

A. Starting equations

Equation (1) can be written for the three key-points of the V-I characteristic: the short-circuit point, the maximum power point, and the open-circuit point.

$$I_{sc} = I_{ph} - I_o\, e^{\frac{I_{sc}\,R_s}{n_s\,V_t}} - \frac{I_{sc}\,R_s}{R_{sh}} \qquad (3)$$

$$I_{mpp} = I_{ph} - I_o\, e^{\frac{V_{mpp}+I_{mpp}\,R_s}{n_s\,V_t}} - \frac{V_{mpp} + I_{mpp}\,R_s}{R_{sh}} \qquad (4)$$

$$I_{oc} = 0 = I_{ph} - I_o\, e^{\frac{V_{oc}}{n_s\,V_t}} - \frac{V_{oc}}{R_{sh}} \qquad (5)$$

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where:

- I_{sc} -short-circuit current in STC
- V_{oc} -open-circuit voltage in STC
- V_{mpp} -voltage at the Maximum Power Point (MPP) in STC
- I_{mpp} -current at the MPP in STC
- P_{mpp} -power at the MPP in STC
- k_i -temperature coefficient of the short-circuit current
- k_v -temperature coefficient of the open-circuit voltage

The above parameters are normally provided by the datasheet of the panel. An additional equation can be derived using the fact that on the P-V characteristic of the panel, at the MPP, the derivative of power with voltage is zero.

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{mpp}\\ I=I_{mpp}}} = 0 \tag{6}$$

So far there are four equations available, but there are five parameters to find, therefore a fifth equation has to be found. For this purpose can be used the derivative of the current with the voltage at short-circuit conditions, which is mainly determined by the shunt resistance R_{sh} [2].

$$\left.\frac{dI}{dV}\right|_{I=I_{sc}} = -\frac{1}{R_{sh}} \tag{7}$$

B. Parameter extraction

From the expression of the current at short-circuit and open-circuit conditions, the photo-generated current I_{ph} and the dark saturation current I_o can be expressed:

$$I_{ph} = I_o\, e^{\frac{V_{oc}}{ns\, V_t}} + \frac{V_{oc}}{R_{sh}} \tag{8}$$

By inserting Eq.(8) into Eq.(3), it takes the form:

$$I_{sc} = I_o \left(e^{\frac{V_{oc}}{ns\, V_t}} - e^{\frac{I_{sc}\, R_s}{ns\, V_t}} \right) + \frac{V_{oc} - I_{sc}\, R_s}{R_{sh}} \tag{9}$$

The second term in the parenthesis from the above equation can be omitted, as it has insignificant size compared to the first term. Than (9) becomes:

$$I_{sc} = I_o\, e^{\frac{V_{oc}}{ns\, V_t}} + \frac{V_{oc} - I_{sc}\, R_s}{R_{sh}} \tag{10}$$

Solving the above equation for I_o, results in:

$$I_o = \left(I_{sc} - \frac{V_{oc} - I_{sc}\, R_s}{R_{sh}} \right) e^{-\frac{V_{oc}}{ns\, V_t}} \tag{11}$$

Eq.(8) and (11) can be inserted into Eq.(4), which will take the form:

$$\begin{aligned} I_{mpp} = I_{sc} &- \frac{V_{mpp} + I_{mpp}\, R_s - I_{sc}\, R_s}{R_{sh}} \\ &- \left(I_{sc} - \frac{V_{oc} - I_{sc}\, R_s}{R_{sh}} \right) e^{\frac{V_{mpp} + I_{mpp}\, R_s - V_{oc}}{ns\, V_t}} \end{aligned} \tag{12}$$

The above expression still contains three unknown parameters: R_s, R_{sh}, and A. The derivative of the power with voltage at MPP can be written as:

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{mpp}\\ I=I_{mpp}}} = \frac{d\,(IV)}{dV} = I + \frac{dI}{dV} V \tag{13}$$

Thereby, to obtain the derivative of the power at MPP, the derivative of Eq.(12) with voltage should be found. However, (12) is a transcendent equation, and it needs numerical methods to express Impp. Eq.(12) can be written in the following form:

$$I = f\,(I, V) \tag{14}$$

where $f(I, V)$ is the right side of (12). By differentiating (14):

$$dI = dI\, \frac{\partial f\,(I, V)}{\partial I} + dV\, \frac{\partial f\,(I, V)}{\partial V} \tag{15}$$

the derivative of the current with voltage results in:

$$\frac{dI}{dV} = \frac{\frac{\partial}{\partial V} f\,(I, V)}{1 - \frac{\partial}{\partial I} f\,(I, V)} \tag{16}$$

From (16) and (13) results:

$$\frac{dP}{dV} = Impp + \frac{Vmpp\, \frac{\partial}{\partial V} f\,(I, V)}{1 - \frac{\partial}{\partial I} f\,(I, V)} \tag{17}$$

From the above:

$$\begin{aligned} \left.\frac{dP}{dV}\right|_{I=I_{mpp}} &= I_{mpp} \\ + V_{mpp} &\frac{-\frac{(I_{sc}\, R_{sh} - V_{oc} + I_{sc}\, R_s) e^{\frac{V_{mpp} + I_{mpp}\, R_s - V_{oc}}{ns\, V_t}}}{ns\, V_t\, R_{sh}} - \frac{1}{R_{sh}}}{1 + \frac{(I_{sc}\, R_{sh} - V_{oc} + I_{sc}\, R_s) e^{\frac{V_{mpp} + I_{mpp}\, R_s - V_{oc}}{ns\, V_t}}}{ns\, V_t\, R_{sh}} + \frac{R_s}{R_{sh}}} \end{aligned} \tag{18}$$

There are two equations now, Eq.(12) and (18), with three unknowns. Eq.(7) can be the used as the third equation. Equations (7), (17) and (18) lead to:

$$\left. -\frac{1}{R_{sh}} \right|_{I=I_{sc}} = \frac{-\frac{(I_{sc}\, R_{sh} - V_{oc} + I_{sc}\, R_s) e^{\frac{I_{sc}\, R_s - V_{oc}}{ns\, V_t}}}{ns\, V_t\, R_{sh}} - \frac{1}{R_{sh}}}{1 + \frac{(I_{sc}\, R_{sh} - V_{oc} + I_{sc}\, R_s) e^{\frac{I_{sc}\, R_s - V_{oc}}{ns\, V_t}}}{ns\, V_t\, R_{sh}} + \frac{R_s}{R_{sh}}} \tag{19}$$

It is possible now to determine all the three unknown parameters, the R_s, A, and R_{sh} using Eq.(12), (18) and (19). As these equations does not allow to separate the unknowns and solve them analytically, they are solved using numerical methods.The flowchart for determining these variables is shown on Fig. 2

III. Construction of the PV full characteristic model

This section describes the construction of a PV panel model, following the logic of the implementation in Matlab.

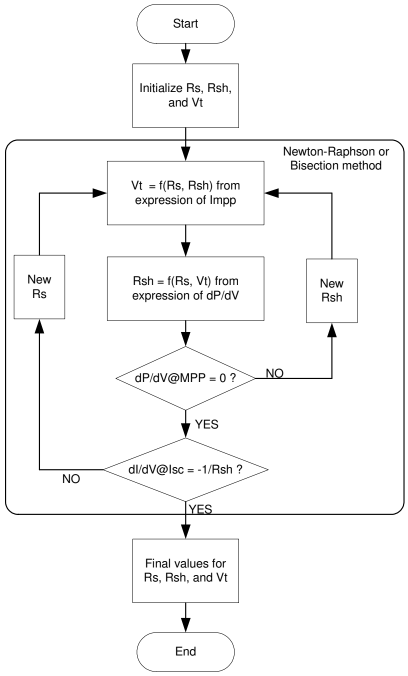

Fig. 2. Flowchart for determination of the PV panel parameters

A. Input parameters

The list of input parameters contains the values from the panel data sheet, as well as the values calculated using data sheet values. Considering the concrete case of the BP-MSX120 panels produced by British Petrol, (installed on the roof of the Green Power Laboratory at Aalborg University) the input data to the model are:

$I_{sc} = 3.87\ (A)$	$k_p = -0.5 \pm 0.05$
$I_{mpp} = 3.56\ (A)$	$n_s = 72;$
$V_{mpp} = 33.7\ (V)$	$R_s = 0.47\ (\Omega)$
$P_{mpp} = 120\ (W)$	$R_{sh} = 1365\ (\Omega)$
$k_v = -0.160 \pm 0.01$	$A = 1.397$

All the above parameters are considered in Standard Test Conditions (STC), and they are given in the product datasheet, except the last three, R_s, R_{sh} and A, which have been calculated from the data-sheet values, as shown in the previous section.

B. Expression of photo-current I_{ph} and dark saturation current I_o

The first equations when constructing the model are the expressions of I_o from (3) and I_{ph} from (5), in STC.

$$I_o = \left(I_{sc} - \frac{V_{oc} - I_{sc}\, R_s}{R_{sh}} \right) e^{-\frac{V_{oc}}{ns\, V_t}} \tag{20}$$

$$I_{ph} = I_o\, e^{\frac{V_{oc}}{ns\, V_t}} + \frac{V_{oc}}{R_{sh}} \tag{21}$$

The above expressions are considered in STC. To include the effects of the environment, e.g. temperature and irradiance, these equations has to be completed with the corresponding terms.

C. The short-circuit current and photo-current irradiance dependence

Both of them are considered to be directly proportional to the irradiation.

$$\begin{aligned} I_{sc}(G) &= I_{sc} G \\ I_{ph}(G) &= I_{ph} G \end{aligned} \tag{22}$$

D. The open-circuit voltage irradiance and temperature dependence

In order to include the irradiance dependence in the equation of V_{oc}, the open-circuit voltage can be expressed from (5):

$$V_{oc}(G) = \ln \left(\frac{I_{ph}(G)\, R_{sh} - V_{oc}(G)}{I_o\, R_{sh}} \right) n_s\ V_t \tag{23}$$

The above equation needs to be solved numerically. Using the Newton-Raphson algorithm, the result can be found after a few iterations, using the open-circuit voltage at STC. The open-circuit voltage shows a linear dependence with the temperature:

$$V_{oc}(T) = V_{oc} + k_v (T - T_{stc}) \tag{24}$$

E. Short-circuit current temperature dependence

The short-circuit current of the PV panel depends linearly on the temperature:

$$I_{sc}(T) = I_{sc}(1 + \frac{k_i}{100}(T - T_{stc})) \tag{25}$$

F. Temperature dependence for the dark saturation current

According to Castañer and Silvestre [5], the dark saturation current does not depend on the irradiance conditions , but it shows a strong dependence with temperature. Similar approach is adopted by Rauschenbach, in [6], where the dark current is considered independent on irradiation. However, the temperature dependence is not discussed there. Castañer and Silvestre give a formula which shows a non-linear dependence with temperature:

$$J_o = B T^{XTI} e^{-\frac{E_g}{kT}} \tag{26}$$

where J_o is the dark saturation current density, B and XTI are constants independent on temperature, and E_g is the semiconductors band gap energy. Xiao et al, in [7] consider that the dark saturation current is dependent on both the irradiance and temperature, and give the following formula for I_o:

$$I_o(G, T) = \frac{I_{ph}(G, T)}{e^{\frac{V_{oc}(T)}{V_t(T)}} - 1} \tag{27}$$

Gow and Manning, in [8], and after them, Walker in [9], use a cubic dependence of I_o on temperature:

$$I_o(T) = I_o(T_1) \left(\frac{T}{T_1} \right)^{\frac{3}{A}} e^{\frac{-qV_g}{nk}(1/T1 - 1/T2)} \tag{28}$$

where $I_o(T_1)$ is the dark current calculated at a given reference (standard) temperature. V_g is the band gap energy of the semiconductor.

G. The proposed method for $I_o(T)$

This work proposes the inclusion of temperature effects in the dark current using a similar approach as in the case of the photo-current in (21) and (30), by updating the parameters of (20) with their corresponding temperature coefficients:

$$I_o(T) = \left(I_{sc}(T) - \frac{V_{oc}(T) - I_{sc}(T)\,R_s}{R_{sh}}\right) e^{-\frac{V_{oc}(T)}{ns\,V_t}} \quad (29)$$

As the expression of I_o in (20) is valid in STC (based on the Shockley equations), it is a natural step to consider it valid also at other temperatures than the STC, as the Shockley equation includes the temperature effects. The temperature dependence of all the parameters in (20) is given in the data sheet.

H. Temperature dependence of the photo-current

The photo-current temperature dependence can be expressed by including in (21) the temperature effect:

$$I_{ph}(T) = I_o(T)\,e^{\frac{V_{oc}(T)}{n_s\,V_t}} + \frac{V_{oc}(T)}{R_{sh}} \quad (30)$$

I. Full-characteristic model

Until this point, temperature and irradiance dependence of the parameters of (1) has been expressed. The parameters in (22), (23), (24), (25), (29), (30) can be inserted in (1) to obtain the I-V relationship of the PV panel, which takes into account the the irradiance and temperature conditions. It should be noted that in order to include in one equation both the irradiation and temperature effects, the principle of superposition is applied.
If one wants to take into account also the reverse characteristics of the PV panel (the second quadrant), e.g. for modeling the effects of partial shading, (1) can be completed with the terms describing the reverse characteristic. In the literature can be found different approaches for modeling the reverse characteristic ([10], [11], [12]), but the most used method is the one described by Bishop in [10]:

$$i = I_{ph} - I_o\,e^{\frac{v+i\,R_s}{n_s\,V_t}} - \frac{(v+i\,R_s)}{R_{sh}}\left(1 + a\left(1 - \frac{v+i\,R_s}{n_s\,V_{br}}\right)^{-m}\right) \quad (31)$$

In the above equation, m is the avalanche breakdown exponent, a is the fraction of the ohmic current in the avalanche breakdown, and V_{br} is the cell junction breakdown voltage [11], [10]. It should be noted that in practice the PV panels have bypass diodes installed, in order to avoid avalanche breakdown of the cells in case of partial shading. Typically is not possible for a panel to enter to the second quadrant of the characteristics, only for individual cells, or a group of cells ($n_s = 1$ and up to several).

IV. Simulation Results

The equations from the previous section has been implemented in Matlab, in order to verify the model in different temperature and irradiance conditions. The results have been compared to the characteristics and values provided by the product data-sheet.

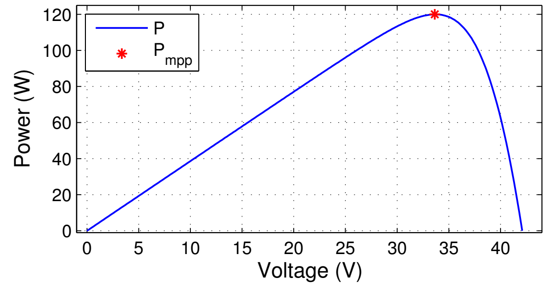

Fig. 3. V-P characteristic of the BP-MSX120 model in STC

The temperature dependencies of the model's V-I curve have been verified by plotting the characteristics for four different temperatures.

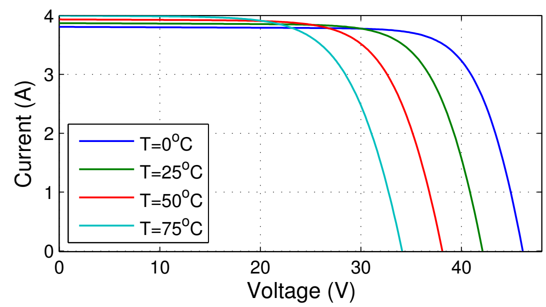

Fig. 4. Voltage-Current characteristics of the PV panel model at four different temperatures and standard irradiation

It can be seen on the above figures, that the short-circuit current, the open-circuit voltage, and the maximum power are in very good agreement with the data-sheet values. The change in the open-circuit voltage and short-circuit current are in accordance with the temperature coefficients given in the data-sheet.

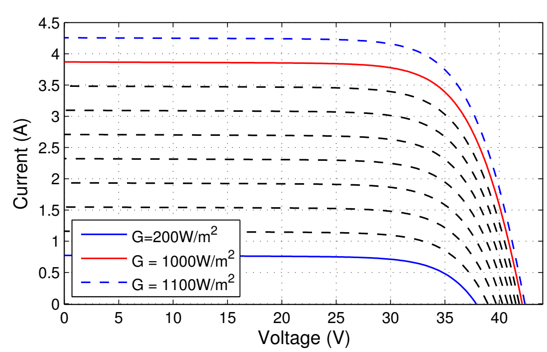

Fig. 5. V-I characteristics of the model at different irradiances and standard cell temperature

From the above figures it can be noted that, according to the theory, the short-circuit current shows a linear dependence with the irradiation, unlike the open-circuit voltage, which

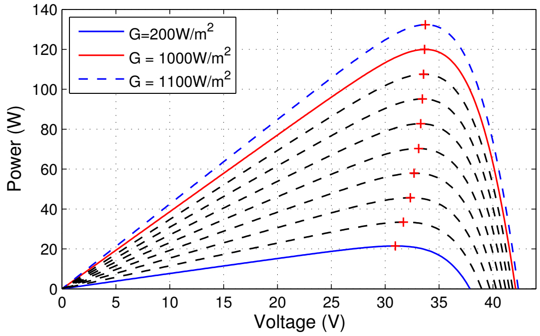

Fig. 6. V-P characteristics of the model at different irradiations and standard temperature

increases logarithmically with the irradiation.
The two-quadrant I-V characteristic of a cell can be plotted by setting the parameters a, m, and V_{br} to the desired values. More details can be found in [10], [12] and [11].

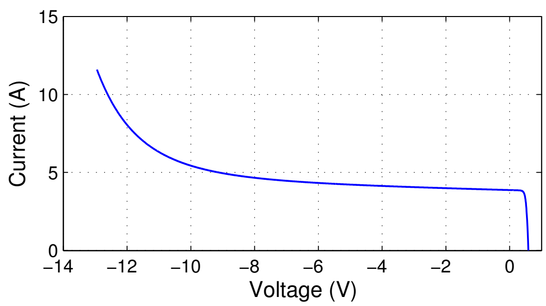

Fig. 7. Full characteristic of a PV cell using the single-diode model

Fig. 8 and 9 show that using the proposed method, the P-V characteristic of the panel is kept within the tolerance limits given in the product datasheet for both 50^oC and 75^oC . The method described in [7] performs similar to the one described here, exceeding with only a small amount the upper tolerance limit at 50^oC. The method presented in [8] predicts a lower power than the tolerance limits of the datasheet, for both considered temperatures.

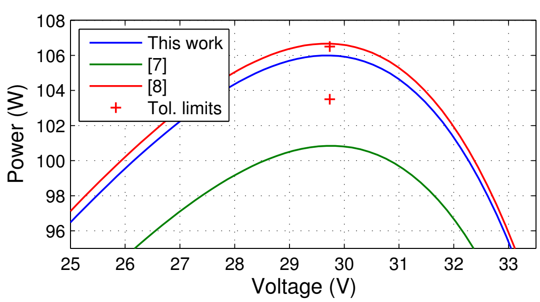

Fig. 8. Simulated P(V) characteristics in the vicinity of MPP using three different methods for temperature dependence of the dark saturation current, at 50^oC

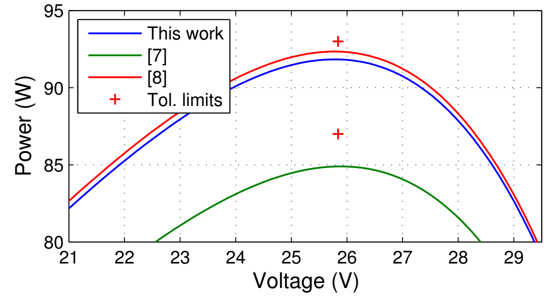

Fig. 9. Simulated P(V) characteristics in the vicinity of MPP using three different methods for temperature dependence of the dark saturation current at 75^oC

V. Conclusions

A model for photovoltaic panels, based exclusively on datasheet parameters has been developed and implemented. The method for extracting the panel parameters from datasheet values has been presented, and the obtained values have been used in the implemented model. The model exhibits a very good agreement with all the specifications given in the product datasheet. A new approach for modeling the temperature dependence of the dark saturation current has been proposed, and compared to the other presented methods. The results show that it gives better correlation with the datasheet values.

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