INTERNAL SERIES RESISTANCE DETERMINATED OF ONLY ONE IV-CURVE UNDER ILLUMINATION

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ABSTRACT: For the measurement of the internal series resistance (which desribes internal losses and losses due to bad contacts as well) two IV-curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891. For single cells and single modules the second IV-curve can be obtained by covering the cell or module with an insect-screen. For large PV-generators (several kW) this method could not be applied. A new method will be presented which allows to determinate the internal series resistance out of only one IV-curve under illumination.

With a new method for the simulation of the second IV-curve, using the effective solar cell equation-method, now it is possible to obtain the internal series resistance out of only one IV-curve measured under illumination.

The method will be presented as well as some experimental results to show the accuracy of the method.

Keywords: Internal Series Resistance - 1: Qualification and Testing - 2: Degradation - 3

1. INTRODUCTION

The principal task of photovoltaic measurement is to monitor the correct function of all components of a PV-system, to detect problems and to iniciate maintenance and repair where necessary, otherwise defects will result in losses in energy yield. As the energy yield decreases if the peak power decreases, the measurement of the peak power of the complete PV-generator is necessary on site under natural ambient conditions [1], [3]. If a decrease of the peak power is detected, an increase of the internal series resistance can be the cause for the decrease of the peak power.

For the determination of the internal series resistance out of one dark IV-curve several methods are known, e.g. [7]. The dark IV-curve can be easily measured for single cells or singele modules. For the measurement of the dark IV-curve an external DC-current source is necessary. Such strong external DC-current sources for large PV-generators (several kW) are very expensive and so hardly available.

For the measurement of the internal series resistance under illumination two IV-curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891 [6]. With a new method for the simulation of the second IV-curve, using the effective solar cell equation-method [2], now it is possible to obtain the internal series resistance out of only one IV-curve measured under illumination.

2. EFFECTIVE SOLAR CELL CHARACTERISTIC

The purpose of I-V-characteristic approximation by means of equivalent circuit diagrams lies in the explicit calculability of matching problems between solar generators and several loads.

A calculation method for matching problems in photovoltaic engineering therefore demands the following options:

- Explicit calculation of current-voltage-characteristic equation V(I)
- Explicit calculation of the parameters of the characteristic equation from the measured parameters I_{sc}, V_{oc}, I_{pmax}, V_{pmax}.
- Degree of accuracy of approximation within the range of degree of accuracy of measuring method (state-of-the-art: 1%)

The “Effective Solar Cell Characteristic” meets all three demanded options, as it has the same approximation accuracy as the two-diodes-model [2].

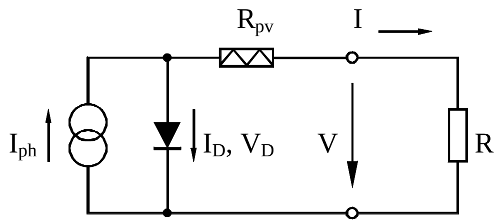

Fig. 1. Equivalent circuit diagram for the effective solar cell characteristic

The equivalent circuit diagram contains a fictitious photoelectric component which presents either a positive or a negative resistance. The new component is to be presented by R_{pv} (photovoltaic resistance).

Important: the true internal series resistance R_s must not be confused with the photovoltaic resistance R_{pv}. The determination of the actual R_s follows in section 3.

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Follows the effective solar cell characteristic:

$$I = I_{ph} - I_0 (e^{\frac{V + I R_{pv}}{V_T}} - 1) \quad (1)$$

Explicit version

$$V = V_T \ln(\frac{I_{ph} - I + I_0}{I_0}) - I R_{pv} \quad (2)$$

With the introduction of the photovoltaic resistance the explicit calculability of matching problems between solar generators and several loads is possible with an accuracy of 1%, related to the maximum power of the solar generator.

For the determination of the 4 independent equation parameters R_{pv}, V_T, I_0, I_{ph} there are also 4 independent measured parameters necessary. In the present case these measured parameters are I_{sc}, V_{oc}, I_{pmax}, V_{pmax}. If in addition the slope M at open-circuit voltage is to be considered

$$M = \frac{dV}{dI}(I = 0) \quad (3)$$

then for the 4 equation parameters 5 equations are available. The following in general valid approximate function for the slope M could be derived [2].

$$M = \frac{V_{oc}}{I_{sc}}(k_1 \frac{I_{p\max} V_{p\max}}{I_{sc} V_{oc}} + k_2 \frac{V_{p\max}}{V_{oc}} + k_3 \frac{I_{p\max}}{I_{sc}} + k_4) \quad (4)$$

with the equation-constants

$$k = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix} \quad (5)$$

Important notice: these equation-constants are not empirical constants, they have been derived by using methods of numerical mathematics, independent of material properties of the solar cell.

Using this nonlinear system of simultaneous equations the equation parameters can be determinated as follows:

$$R_{pv} = -M \frac{I_{sc}}{I_{p\max}} + \frac{V_{p\max}}{I_{p\max}}(1 - \frac{I_{sc}}{I_{p\max}}) \quad (6)$$

$$V_T = -(M + R_{pv}) I_{sc} \quad (7)$$

$$I_0 = I_{sc} e^{\frac{-V_{oc}}{V_T}} \quad (8)$$

$$I_{ph} = I_{sc} \quad (9)$$

Example 1: Monocrystalline PV-Module BP585F:

Check of approximation quality of the effective solar cell characteristic: Comparison with measured values.

$$\begin{aligned} I_{sc} &= 1.015\,A \\ V_{oc} &= 20.508\,A \\ I_{p\max} &= 0.951\,A \\ V_{p\max} &= 17.002\,V \end{aligned} \quad M = -1.535\frac{V}{A} \quad \begin{aligned} R_{pv} &= 0.431\Omega \\ V_T &= 1.12V \\ I_0 &= 1.142 \cdot 10^{-8}\,A \\ I_{ph} &= 1.015\,A \end{aligned} \quad (10)$$

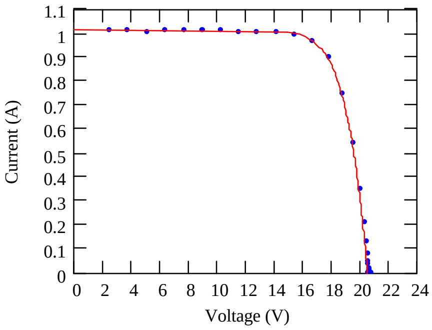

Fig.2. IV-curve approximation of a crystalline PV-module

Example 2: Amorphous PV-module Solarex MSX 40:

Check of approximation quality of the effective solar cell characteristic: Comparison with measured values.

$$\begin{aligned} I_{sc} &= 2.874\,A \\ V_{oc} &= 22.662\,A \\ I_{p\max} &= 2.099\,A \\ V_{p\max} &= 14.653\,V \end{aligned} \quad M = -2.454\frac{V}{A} \quad \begin{aligned} R_{pv} &= 0.906\ \Omega \\ V_T &= 4.804\ V \\ I_0 &= 0.026\ A \\ I_{ph} &= 2.874\ A \end{aligned} \quad (11)$$

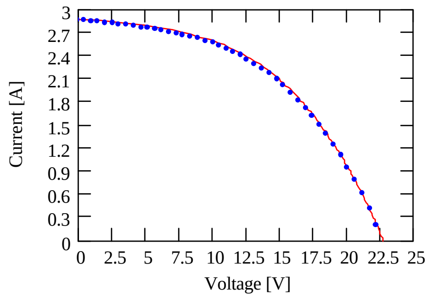

Fig.3. IV-curve approximation of an amorphous PV-module

Fig. 2 and Fig.3. show both the good accord of the measured I-V-curves with the effective solar cell characteristic.

3. INTERNAL SERIES RESISTANCE DETERMINATED OF TWO IV-CURVES

For the measurement of the internal series resistance (which desribes internal losses and losses due to bad contacts as well) two IV-curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891 [6].

From the two characteristics two working points V_1 and V_2 have to be obtained of which the series resistance can be calculated.

The two working points are determinated as follows: Definition of a current interval ΔI. Here:

$$\Delta I = 0.5 \cdot I_{sc2} \tag{12}$$

Determination of the working points V_1 and V_2 with equation (2)

$$V_1=V(I_{sc1}-\Delta I, R_{pv1}, V_{T1}, I_{01}, I_{ph1}) \tag{13}$$

$$V_2=V(I_{sc2}-\Delta I, R_{pv2}, V_{T2}, I_{02}, I_{ph2}) \tag{14}$$

Calculation of the series resistance

$$R_s = \frac{V_2 - V_1}{I_{sc1} - I_{sc2}} \tag{15}$$

For single cells and single modules the second IV-curve can be obtained by covering the cell or module with an insect-screen.

Fig.4. R_s-Measurement of single PV-Modules

For large PV-generators (several kW) this method could not be applied. A new method is here necessary which allows to determinate the internal series resistance out of only one IV-curve under illumination.

4. INTERNAL SERIES RESISTANCE DETERMINATED OF ONLY ONE IV-CURVE UNDER ILLUMINATION

Degradation of peak power can be caused by an increase of the internal series resistance.

For the determination of the internal series resistance out of one dark IV-curve several methods are known, e.g. [7]. The dark IV-curve can be easily measured for single cells or singele modules. As for the measurement of the dark IV-curve an external DC-current source is necessary, such strong external DC-current sources for large PV-generators (several kW) are very expensive and so hardly available.

For the measurement of the internal series resistance two IV-curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891 [6]. As the actual spectrum during the measurement is not relevant for the calculation of R_s, the measurement of the first characteristic can also take place under open air conditions with natural sunlight.

The second characteristic can be obtained by the following simulation, so a second measurement is unnecessary.

Characteristic 1: Measurement

$$I_{sc1} \quad V_{oc1} \quad I_{p\max1} \quad V_{p\max1} \tag{16}$$

Characteristic 2: Simulation

$$FF = \frac{I_{p\max1} \cdot V_{p\max1}}{I_{sc1} \cdot V_{oc1}}$$

$$f_i = \begin{cases} FF \quad if \quad FF \geq 0.7 \\ 2.2 \cdot 10^{-9} \cdot e^{28 \cdot FF} \quad otherwise \end{cases} \tag{17}$$

$$f_v = 1 \longrightarrow no\ change\ in\ Voltage \tag{18}$$

FF is the same for both characteristcs, so:

$$I_{sc2} = f_i \cdot I_{sc1}$$

$$V_{oc2} = V_{oc1}$$

$$I_{p\max2} = f_i \cdot I_{p\max1}$$

$$V_{p\max2} = V_{p\max1} \tag{19}$$

The determination of the series resistance R_s of only one measured IV-characteristic now is possible.

The following example shows the accuracy of this method.

In order to demonstrate the effect of a higher R_s, the R_s of a BP585F-module first was measured without any manipulation and then a second measurement with an additional external resistor R_{ext}=0.9 Ω was made.

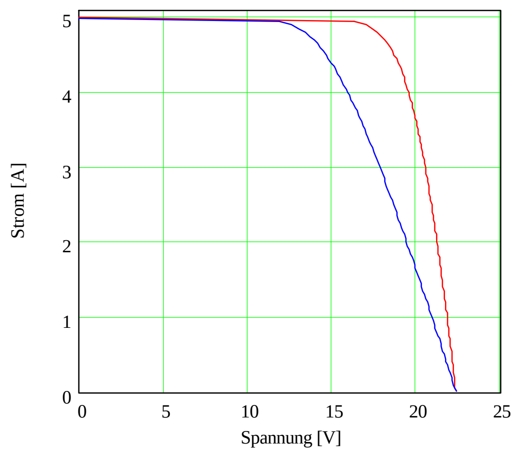

Fig. 5. BP 585F with(left) and without(right) R_s-manipulation

Measurement A without manipulation:

$$\left.\begin{array}{ll} I_{scA} = 5\,A & V_{ocA} = 22.3\,V \\ I_{p\max A} = 4.72\,A & V_{p\max A} = 18\,V \end{array}\right\} R_{sA} = 0.4\,\Omega \qquad (20)$$

Measurement B with manipulation $+R_{ext}$=0.9Ω

$$\left.\begin{array}{ll} I_{scB} = 5\,A & V_{ocB} = 22.3\,V \\ I_{p\max B} = 4.51\,A & V_{p\max B} = 14.56\,V \end{array}\right\} R_{sB} = 1.3\,\Omega \qquad (21)$$

The manipulation can be detected here.

5. SUMMARY

Degradation of peak power P_{pk} can be caused by an increase of the internal series resistance R_s.

There exist 2 causes for the increase of the R_s of a generator string:

1. Degradation of the PV-module leads to a higher R_s of the module.
2. Faulty installation leads to a higher R_s of the whole string.

In the first case, the manufacturer of the PV-Modules is responsible for the fault.

In the second case it is the technical firm which installed the PV-generator.

Now the R_s of a single PV-module can be compared with the R_s of the whole string by the measurement of only one I-V-curve under illumination.

So the true reason for the problem can be identified.

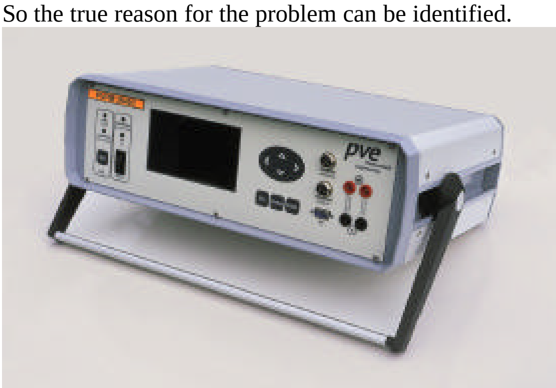

Fig. 6. PVPM: P_{pk} and R_s Measuring Device and Curve Tracer for PV-Modules and Strings. www.pv-engineering.de

The difference between the R_s of the whole string and the sum of the single PV-module-R_s (which can be obtained by measurement or by the calculation of the datasheet-R_s) shows the quality of the wiring.

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