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

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ABSTRACT: For the measurement of the internal series resistance (which describes 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 determine 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 initiate 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 single 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 \( I_{ph} \), \( V_{oc} \), \( I_{pmax} \), \( V_{pmax} \).
- Degree of accuracy of approximation within the range of the 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](image)

The equivalent circuit diagram contains a fictitious photovoltaic 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.
Follows the effective solar cell characteristic:
\[ I = I_{ph} - I_0 \left( e^{\frac{V}{V_T}} - 1 \right) \]  
(1)

Explicit version
\[ V = V_T \ln \left( \frac{\frac{1}{I_0} - 1 + \frac{1}{I_{ph}}}{I_0} \right) - IR_{pv} \]  
(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
\[ M = \frac{dV}{dI} \]  
(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].
\[ M = \frac{V}{I_{sc}} \left( k_1 \frac{I_{pmax}}{I_{sc}} V_{pmax} + k_2 \frac{V_{pmax}}{V_{oc}} + k_3 \frac{I_{pmax}}{I_{sc}} + k_4 \right) \]  
(4)

with the equation-constants
\[ k = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix} \]  
(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 determined as follows:
\[ R_{pv} = -M \frac{I_{sc}}{I_{pmax}} + \frac{V_{pmax}}{I_{pmax}} \left( 1 - \frac{I_{sc}}{I_{pmax}} \right) \]  
(6)
\[ V_T = -(M + V_{pv}) I_{sc} \]  
(7)
\[ I_0 = I_{sc} e^{\frac{V}{V_T}} \]  
(8)
\[ I_{ph} = I_{sc} \]  
(9)

Example 1: Monocrystalline PV-Module BP585F:
Check of approximation quality of the effective solar cell characteristic: Comparison with measured values.

\[ I_{sc} = 1.015 \text{A} \]
\[ V_{oc} = 20.508 \text{A} \]
\[ I_{pmax} = 0.951 \text{A} \]
\[ V_{pmax} = 17.002 \text{V} \]
\[ R_{pv} = 0.431 \text{Ω} \]
\[ M = -1.535 \frac{V}{A} \]
\[ V_T = 1.12 \text{V} \]
\[ I_0 = 1.142 \times 10^{-5} \text{A} \]

Example 2: Amorphous PV-module Solarex MSX 40:
Check of approximation quality of the effective solar cell characteristic: Comparison with measured values.

\[ I_{sc} = 2.874 \text{A} \]
\[ V_{oc} = 22.662 \text{A} \]
\[ I_{pmax} = 2.099 \text{A} \]
\[ V_{pmax} = 14.653 \text{V} \]
\[ R_{pv} = 0.906 \text{Ω} \]
\[ M = -2.454 \frac{V}{A} \]
\[ V_T = 4.804 \text{V} \]
\[ I_0 = 0.026 \text{A} \]

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 DETERMINED OF TWO IV-CURVES

For the measurement of the internal series resistance (which describes 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 determined as follows: Definition of a current interval \( \Delta I \). Here:

\[
\Delta I = 0.5 \cdot I_{sc2}
\]  

(12)

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

\[
V_1 = V(I_{sc1} - \Delta I, R_{pv1}, V_{T1}, I_01, I_{ph1})
\]  

(13)

\[
V_2 = V(I_{sc2} - \Delta I, R_{pv2}, V_{T2}, I_02, I_{ph2})
\]  

(14)

Calculation of the series resistance

\[
R_s = \frac{V_2 - V_1}{I_{sc1} - I_{sc2}}
\]  

(15)

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

4. INTERNAL SERIES RESISTANCE DETERMINED 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 single 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

\[
I_{sc1} V_{oc1} I_{p_{max1}} V_{p_{max1}}
\]  

(16)

Characteristic 2: Simulation

\[
FF = \frac{I_{p_{max1}} V_{p_{max1}}}{I_{sc1} V_{oc1}}
\]

\[
f_1 = \begin{cases} FF & \text{if } FF \geq 0.7 \\ 2.2 \cdot 10^{-9} \cdot e^{20FF} & \text{otherwise} \end{cases}
\]  

(17)

\[
f_1 = 1 \rightarrow \text{no change in Voltage}
\]  

(18)

\[
I_{sc2} = f_1 \cdot I_{sc1}
\]

\[
V_{oc2} = V_{oc1}
\]

\[
I_{p_{max2}} = f_1 \cdot I_{p_{max1}}
\]

\[
V_{p_{max2}} = V_{p_{max1}}
\]  

(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 $R_{ext}=0.9\ \Omega$ was made.

![Graph showing I-V characteristics with and without manipulation](image)

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

Measurement A without manipulation:

\[
I_{\text{max A}} = 5\ A \quad V_{\text{oc A}} = 22.3\ V \quad I_{\text{pmax A}} = 4.72\ A \quad V_{\text{pmax A}} = 18\ V \Rightarrow R_{sA} = 0.4\ \Omega
\]

(20)

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

\[
I_{\text{max B}} = 5\ A \quad V_{\text{oc B}} = 22.3\ V \quad I_{\text{pmax B}} = 4.51\ A \quad V_{\text{pmax B}} = 14.56\ V \Rightarrow R_{sB} = 1.3\ \Omega
\]

(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.

![Image of PVPM: $P_{pk}$ and $R_s$ Measuring Device and Curve Tracer for PV-Modules and Strings](image)

**Fig. 6.** PVPM: $P_{pk}$ and $R_s$ Measuring Device and Curve Tracer for PV-Modules and Strings.

[www.pv-engineering.de](http://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.

6. REFERENCES


[8] [www.pv-engineering.de](http://www.pv-engineering.de) Several publications.