Abstract – Quality inspection of PV-modules includes measurement of peak-power $P_{pk}$ and internal series resistance $R_s$. Peak-power is defined as maximum power under standard test conditions (STC). As the peak-power can decrease due to degradation effects, a continuous quality inspection has to be realized on-site under natural ambient conditions. Losses in the PV-modules can be described by an internal series resistance $R_s$. An increasing $R_s$ shows internal losses as well as degrading contacts. A measuring method is presented, which can measure under natural ambient conditions and directly display the results peak-power $P_{pk}$ and internal series resistance $R_s$. I-V-characteristics measured under ambient conditions can be corrected concerning temperature and irradiation according to IEC 60891. The description of the characteristic by the “effective solar cell characteristic” makes it possible to explicitly carry out the calculations for $P_{pk}$, IEC 60891 also describes a method for the evaluation of the internal series resistance $R_s$. A graphic method is used in order to determine certain points in the I-V-characteristic, which serve as input-values for the calculation of the series resistance. The accuracy of this graphic method is limited by the accuracy of the graphically determined points. Using the method of the “effective solar cell characteristic” it is possible to explicitly calculate the demanded points of the I-V-characteristic, thus being capable of explicit calculation of the series resistance $R_s$. The method of the “effective solar cell characteristic” is presented as well as some significant results concerning $P_{pk}$- and $R_s$-measurement under natural ambient conditions.

1. INTRODUCTION

Quality inspection of PV-Modules under natural ambient conditions is a necessary service for users of photovoltaic equipment, considering a guarantee period of up to 10 years or even more. The operating behaviour of a solar cell is described by its current-voltage-characteristic (I-V-characteristic). By measurement of present I-V-characteristics under natural ambient conditions, the correct functioning of a solar generator, consisting of one or several modules, can be shown (Schulte K.M. et al 1993). Deviations of the I-V-characteristic from the theoretically expected characteristic permit to draw conclusions concerning internal interruptions, partial shadings, mismatching etc. In addition to the present operating behaviour, informations about possible degradation processes should be obtained. Measurement of stationary characteristic features such as peak power and internal series resistance are necessary. Measurement of peak-power $P_{pk}$ needs standard test conditions (STC, IEC 60904–3), which demand a very high effort for the test equipment, which leads in addition to high costs per measurement. Also the experimental effort for the measurement of the internal series resistance $R_s$ in a laboratory is rather high. Measurements of $P_{pk}$ and $R_s$ under natural ambient conditions need mathematical corrections of the measured I-V-characteristic, considering irradiance and cell temperature. For the description of the I-V-characteristic of solar cells there exist several equivalent circuit diagrams with their affiliated I-V-characteristic equations, of which a suitable one for the mathematical correction of the I-V-characteristic to STC shall be selected.

2. EFFECTIVE SOLAR CELL CHARACTERISTIC

2.1. Demands on solar cell equivalent circuit diagrams.
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 photovoltaik 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 $I_{oc}$, $V_{oc}$, $I_{pmax}$, $V_{pmax}$
- Degree of accuracy of approximation within the range of degree of accuracy of measuring method (state-of-the-art: 1%)
2.2 Existing equivalent circuit diagrams.

From the following equivalent circuit diagrams in stationary condition that one shall be selected, which meets all three mentioned options:

Fig. 2. Ideal model.
Low approximation accuracy.

\[
I = I_{ph} - I_0 \left( e^{\frac{V}{VT}} - 1 \right)
\]

\[
V = V_T \ln \left( \frac{I_{ph} - I + I_0}{I_0} \right)
\]

Fig. 3. Simple model
Good approximation accuracy.

\[
I = I_{ph} - I_0 \left( e^{\frac{V}{VT}} - 1 \right)
\]

\[
V = V_T \ln \left( \frac{I_{ph} - I + I_0}{I_0} \right) - IR_s
\]

Value for \( R_s \) can become negative.

Fig. 4. Standard model
Good approximation accuracy.

\[
I = I_{ph} - I_0 \left( e^{\frac{V + IR_s}{VT}} - 1 \right) - \frac{V + IR_s}{R_p}
\]

\[V=\text{?}\] explicit solution unknown.

Fig. 5. Two-diodes-model
Very good approximation accuracy.

\[
I = I_{ph} - I_0 \left( e^{\frac{V + IR_p}{VT}} - 1 \right) - \frac{V + IR_s}{R_p}
\]

None of the 4 presented equivalent circuit diagrams (Fig.2 to Fig.5) meets all three demanded options.

The interesting thing about the simple model of Fig.3 is the very good approximation accuracy which reaches the approximation accuracy of the two-diodes-model, if a negative answer for the series resistance is accepted. (Wagner A. 1999). As negative resistors do not exist in reality, the component in the equivalent circuit diagram cannot be an ohmic resistance.

The equivalent circuit diagram has to be modified by a fictitious photoelectric component which presents either a positive or a negative resistance.

The new component is to be presented by \( R_{pv} \) (photovoltaik resistance).

Important: the true internal series resistance \( R_s \) must not be confused with the photovoltaik resistance \( R_{pv} \).

Fig. 6. Equivalent circuit diagram for the effective solar cell characteristic

Follows the effective solar cell characteristic:

\[
I = I_{ph} - I_0 \left( e^{\frac{V + IR_p}{VT}} - 1 \right)
\]

Explicit version

\[
V = V_T \ln \left( \frac{I_{ph} - I + I_0}{I_0} \right) - IR_{pv}
\]

With the introduction of the photovoltaik 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.
2.3 Parameters of the characteristic equation.

For the determination of the 4 independent equation parameters \( R_{pv}, V_{oc}, I_0, I_{ph} \) 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 (Fig. 1)

\[
M = \frac{dV}{dI}(I = 0)
\]  

then for the 4 equation parameters 5 equations are available:

\[
V(I = 0) = V_{oc}
\]  

\[
V(I = I_{sc}) = 0
\]  

\[
V(I = I_{pmax}) = V_{pmax}
\]  

\[
\frac{d(V \cdot I)}{dI}(I = I_{pmax}) = 0
\]  

\[
\frac{dV}{dI}(I = 0) = M
\]  

Using this nonlinear system of simultaneous equations the equation parameters can approximately be determined as follows (Wagner A. 1999):

\[
R_{pv} = -\frac{M}{I_{pmax}} \frac{I_{sc}}{I_{pmax}} + \frac{V_{pmax}}{I_{pmax}} (1 - \frac{I_{sc}}{I_{pmax}})
\]  

\[
V_T = -(M + R_{pv})I_{sc}
\]  

\[
I_0 = I_{sc} e^{-\frac{V_T}{T}}
\]  

\[
I_{ph} = I_{sc}
\]

Condition for the calculation of the 4 equation parameters is the existence of the 5 measured parameters \( I_{sc}, V_{oc}, I_{pmax}, V_{pmax} \) \( M \) with sufficient accuracy.

Normally the 4 parameters \( I_{sc}, V_{oc}, I_{pmax}, V_{pmax} \) can be obtained with a measuring error \(<1\%\). The measurement of the slope \( M \) however is more difficult and so contains a higher systematic measuring error.

As with the simultaneous equations (10), (11), (12), (13) and the 4 measured parameters \( I_{sc}, V_{oc}, I_{pmax}, V_{pmax} \) the equation parameters \( R_{pv}, V_T, I_0, I_{ph} \) can be calculated straight-forward, and as consequently the slope \( M \) can be calculated straight-forward with (8) there must exist a straight-forward function

\[
M = f(I_{sc}, V_{oc}, I_{pmax}, V_{pmax})
\]

The following in general valid approximate function for the slope \( M \) could be derived, which as a result allows the application of the effective solar cell equation with an accuracy of \( 1\% \) (Wagner A. 1999).

\[
M = \frac{V_{oc}}{I_{sc}} \left( k_1 \frac{I_{pmax}}{I_{sc}} \frac{V_{pmax}}{V_{oc}} + k_2 \frac{V_{pmax}}{V_{oc}} + k_3 \frac{I_{pmax}}{I_{sc}} + k_4 \right)
\]

with the equation-constants.

\[
k = \begin{pmatrix}
-5.411 \\
6.450 \\
3.417 \\
-4.422
\end{pmatrix}
\]

The following example shows the working point of a resistor \( R_L \) at direct connection to the solar module.

What a resistor has to be connected in order to cause a current of \( I_L = 2A \)?

\[
\begin{align*}
I_{sc} &= 3.65A \\
V_{oc} &= 21.7A \\
I_{pmax} &= 3.15A \\
V_{pmax} &= 17.5V \\
R_{pv} &= -0.624\Omega \\
V_T &= 3.09V \\
I_0 &= 3.253mA \\
I_{ph} &= 3.65A
\end{align*}
\]

with eq. (8) follows \( V(I_L = 2A) = 20.5V \)

\[
R_L = 10.25\Omega
\]

Fig. 7. Resistor as load of a solar module
3. SERIES RESISTANCE

3.1 Measuring method

The international standard IEC 60 891 prescribes the following procedures for temperature and irradiance corrections to measured I-V-characteristics of crystalline silicon photovoltaik devices.

For the determination of the series resistance \( R_s \) under simulated sunlight the following conditions have to be kept:

- At ambient temperature 2 characteristics are measured at different irradiances (of which the extent does not need to be known) but of the same spectral distribution.
- In the course of the measurement the temperature of the cells must be kept constant (permissible tolerance \( \pm 2^\circ C \)).

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 international standard IEC 60 891 prescribes the following procedure for the determination of the two working points:

- Definition of current interval \( \Delta I \) between short-circuit current and the current in the selected working point of the characteristic 2 (where index 2 indicates the characteristic with the lower short-circuit current)
  \[
  \Delta I = 0.5 \cdot I_{02} \tag{24}
  \]

- Determination of the working points \( V_1 \) and \( V_2 \) with equation (8)
  \[
  V_1 = V(I_{sc1} - \Delta I, R_{pv1}, V_T1, I_01, I_{ph1}) \tag{25}
  \]
  \[
  V_2 = V(I_{sc2} - \Delta I, R_{pv2}, V_T2, I_02, I_{ph2}) \tag{26}
  \]

- Calculation of the series resistance
  \[
  R_s = \frac{V_2 - V_1}{I_{02} - I_{01}} \tag{27}
  \]

As the actual spectrum during the measurement is not relevant for the calculation of \( R_s \), the measurement can also take place under open air conditions with natural sunlight.

The condition of unchanged spectral distribution can be kept by a short measurement interval for the two characteristics (\( \Delta T < 1 \text{ min} \)).

The change of irradiance without change of spectral distribution can be obtained by decrease of transmission by an extensive filter, which is put above the PV-module immediately after the first measurement without filter.

As a filter a close-meshed screen is applied with a mesh-distance of about 5 mm. Thus the spectrum keeps unchanged.

3.2 Exemplary measuring result

The determination of the internal series resistance is to be demonstrated with the example of the following measurement.

**Measurement 1**

- \( I_{sc1} = 1.998A \)
- \( V_{ov1} = 22.235A \)
- \( M = -1.652 \frac{V}{A} \)
- \( V_T1 = 1.488V \)
- \( I_{p1} = 6.442 \cdot 10^{-7} A \)
- \( V_{p1} = 16.977V \)
- \( I_{p1} = 1.998 A \)

**Measurement 2**

- \( I_{sc2} = 0.795A \)
- \( V_{ov2} = 20.958A \)
- \( M = -2.551 \frac{V}{A} \)
- \( V_{T2} = 1.455V \)
- \( I_{p2} = 4.402 \cdot 10^{-7} A \)
- \( V_{p2} = 16.798V \)
- \( I_{p2} = 0.795 A \)

Fig. 8 shows the measured points of the characteristic as well as the calculated effective solar cell characteristic, calculated with eq. (8).

**Definition of current interval with eq. (24)**

\[
\Delta I = 0.5 \cdot I_{02} = 0.398A \tag{30}
\]

**Determination of the working point \( V_1 \) with eq. (8)**

\[
V_1 = V(I_{sc1} - \Delta I, R_{pv1}, V_T1, I_01, I_{ph1}) = 18.38V \tag{31}
\]

**Determination of the working point \( V_2 \) with eq. (8)**

\[
V_2 = V(I_{sc2} - \Delta I, R_{pv2}, V_T2, I_02, I_{ph2}) = 19.663V \tag{32}
\]

**Internal series resistance**

\[
R_s = \frac{19.663V - 18.38V}{1.998A - 0.795A} \tag{33}
\]

\[
R_s = 1.067\Omega \tag{34}
\]
4. PEAK POWER

4.1 Measuring method

Peak power is the maximum power under standard test conditions (STC)

\[ P_{pk} = P_{\text{max}}(E_0, T_{j0}) \]  

(35)

Standard Test Conditions (STC):

- Irradiance \( E_0 = 1000 \text{ W/m}^2 \)  
  \( \text{(36)} \)
- Solar spectrum AM 1.5  
  \( \text{(37)} \)
- Solar cell temperature \( T_{j0} = 25 \^\circ \text{C} (= 298 \text{ K}) \)  
  \( \text{(38)} \)

The actual maximum power point (MPP) varies with irradiance and temperature. Measurement of peak power under natural ambient conditions means correction of the actual MPP to STC.

Not only the irradiance, but also the spectral distribution of the irradiance has an important influence on the efficiency of the solar cell. The spectral response of the solar cell is expressed by its short-circuit current.

Proposition: For a linear description of the spectral response a spectrally assessed effective irradiance is to be introduced.

Definition: The effective irradiance for a solar cell only consists of that part of the solar spectrum which takes part in energy-conversion in this solar cell. By analogy with the unit Lux (lx) of lighting technology, where brightness is spectrally assessed by the spectral sensibility of the human eye, it is proposed here to describe the spectral sensibility of the photovoltaic solar cell by an effective irradiance with the new unit “Photovoltaic Lux” (phox). The short-circuit current of the solar cell is a linear measure for the effective irradiance.

At AM 1.5 applies

\[ E_{\text{eff}} = E \]

\[ \text{phox} = \frac{W}{m^2} \]  

(39)

Beyond AM 1.5 applies

\[ E_{\text{eff}} = I_{phox} \cdot K_{\text{phox}} \]  

(40)

The solar module to be measured serves as its own “phox-meter” when its phox-constant \( K_{\text{phox}} \) is known. The phox-constant can be measured at AM 1.5-conditions at a clear day under natural ambient conditions.

AM 1.5 applies, when for the radiation angle applies

\[ \cos(\Theta_z) = \frac{1}{AM} \]  

(41)

follows for AM=1.5

\[ \cos(\Theta_z) = \frac{1}{1.5} \]  

(42)

The times, at which this radiation angle applies, can be determined with known date of the year and geographic position. (Duffie J.A., Beckman W.A. 1980).

Example: Dortmund (\( \lambda = -7^\circ \) east. longitude, \( \varphi = 51^\circ \) north. latitude) August 17. (Wagner A. 1999)

Results in Central European Summer Time

\[ AM = 1.5(\text{am}) \quad 11\text{h} 9\text{min} \]  

(43)

\[ AM = 1.5(\text{pm}) \quad 16\text{h} 4\text{min} \]  

(44)

For the determination of the phox-constant, at AM 1.5-conditions the irradiance has to be measured with a pyranometer as well as the actual short-circuit current of the solar module.

\[ K_{\text{phox}} = \frac{E_{\text{AM1.5}}}{I_{\text{AM1.5}}} \]  

(45)

With the known phox-constant for the module to be measured an additional measurement of the irradiance is not necessary. All further calculations will refer to the “effective irradiance” \( E_{\text{eff}} \) measured in phox.

For the determination of the peak-power of a PV-module first its phox-constant must be known. With the known phox-constant, an actual characteristic of the module can be measured any time. Now the actual effective characteristic parameters can be evaluated.

With the cell-temperature \( T_j \) and the temperature coefficient \( c_T \) of power, the expected peak-power now can be calculated (Wagner A. 1999).

Correction to STC:

\[ I_{\rho_{\text{max}}} = I_{\rho_{\text{max}}} \frac{E_0}{E_{\text{eff}}} \]  

(46)

\[ V_{\rho_{\text{max}}} = \frac{V_{\rho_{\text{max}}}}{1 + c_T(T_j - T_{j0})} \]

\[ + \frac{T_j}{T_{j0}} \ln\left(\frac{E_{\text{eff}}}{E_0}\right) - I_{\rho_{\text{max}}} R_{\rho}(\frac{E_{\text{eff}}}{E_0} - 1) \]

follows the peak-power

\[ P_{pk} = I_{\rho_{\text{max}}} \cdot V_{\rho_{\text{max}}} \]  

(47)

For a complete presentation of the I-V-characteristic under STC the following relations can be used.

\[ I_{\text{sc}} = I_{\text{sc}} \frac{E_0}{E_{\text{eff}}} \quad V_{\text{sc}} = V_{\text{sc}} \frac{V_{\text{max}}}{V_{\text{max}}} \]  

(48)
For the application of formula (46) two additional informations are necessary.

- Temperature coefficient $c_T$ of power
- Cell temperature $T_j$

The temperature coefficient $c_T$ of power has to be adopted from the data-sheet of the PV-module. If no informations are available, the following value can be used as default value for crystalline silicon cells:

$$c_T = -0.0044 \text{ K}^{-1}$$  (49)

The error rate of the evaluated peak power due to error in temperature coefficient $c_T$ is shown in Fig. 9.

Follows the cell temperature, depending on irradiance and ambient temperature.

$$T_j(E_{eff}, T_{amb}) = T_{amb} + (NOCT - T_{amb}) \frac{E_{eff}}{E_N}$$  (54)

The error rate of the evaluated peak power due to error in evaluated cell temperature $T_j$ is shown in Fig. 10.

4.2. Exemplary measuring result
The measurement of the first characteristic of Fig. 8 for $R_s$-determination has been made at the following effective irradiance:

$$E_{eff1} = 777 \text{ phox}$$  (55)

In order to reduce irradiance without changing the spectrum, a close-meshed screen is applied over the PV-module. So the effective irradiance is reduced by the factor

$$k = \frac{I_{sc2}}{I_{sc1}} = 0.398$$  (56)

Follows

$$E_{eff2} = 309 \text{ phox}$$  (57)

The following temperature has been determined:

$$T_j = 294 \text{ K}$$  (58)

Remark: as both measurements have been carried out within a short time interval, and in addition, the cell-temperature does not change in a sharp rise due to the close-meshed screen, the cell temperature is approximately the same in both cases.
For the calculation of the peak power with the formulas (45), (46) and (47) the following values have been used:

Measurement 1

\[
I_{p_{\text{max}}} = 1.821 A
\]
\[
V_{p_{\text{max}}} = 16.977 V
\]
\[
V_{T_1} = 1.488 V
\]
\[
R_{p_{\text{1}}} = 0.908 \Omega
\]
\[
T_{j_1} = 294 K
\]
\[
E_{\text{eff1}} = 777 \text{ phox}
\]

Measurement 2

\[
I_{p_{\text{max2}}} = 0.730 A
\]
\[
V_{p_{\text{max2}}} = 16.798 V
\]
\[
V_{T_2} = 1.455 V
\]
\[
R_{p_{\text{2}}} = 0.721 \Omega
\]
\[
T_{j_2} = 294 K
\]
\[
E_{\text{eff2}} = 309 \text{ phox}
\]

In the present case the measurement concerns a polycrystalline module, year of production 1991.


Data-sheet informations:

- Peak-power \( P_{p_{\text{pk}}} = 50 \text{ W} \), Tolerance \( \pm 10\% \).
- Losses due to degradation in 10 years <10%.
- With the guaranteed least power at delivery date of 45W and degradation-losses <5W after 10 years follows the acceptable least peak-power of 40 W. In the present case the 10-years-guarantee is satisfied.

5. CONCLUSIONS

The description of the operating behaviour of solar cells by the effective solar cell characteristic allows explicit calculation of the parameters of the effective solar cell characteristic from the measured parameters \( I_{sc}, V_{oc}, I_{p_{\text{max}}}, V_{p_{\text{max}}} \) with an accuracy of 1%, related to the maximum power of the solar generator.

The explicit calculation of the internal series resistance \( R_s \) now becomes possible and replaces the graphic method postulated in IEC 60891.

For \( R_s \) measurement we need two I-V-characteristics of same temperature but different irradiances. The change of irradiance without change of spectral distribution can be obtained by decrease of transmission by an extensive filter (close-meshed screen). The filter is put above the PV-module after the first measurement without filter.

For the determination of the peak-power a new description of the irradiance is proposed. By analogy with the unit Lux (lx) of lighting technology it is proposed here to describe the spectral sensibility of the photovoltaik solar cell by an effective irradiance with the new unit “Photovoltaic Lux” (phox).

**NOMENCLATURE**

- AM Air Mass
- \( c_T \) Temperature coefficient of power
- \( E \) Irradiance (W/m\(^2\))
- \( E_0 \) 1000 W/m\(^2\) (Irradiance at STC)
- \( E_{\text{eff}} \) Effective irradiance (phox)
- \( E_N \) 800 W/m\(^2\) (Irradiance for NOCT)
- \( I \) Current (A)
- \( I_0 \) Reverse current (A)
- \( I_D \) Diode-current (A)
- \( I_L \) Current at actual working point (A)
- \( I_{ph} \) Photo-current (A)
- \( I_{p_{\text{max}}} \) Current at MPP (A)
- \( I_{sc} \) Short-circuit current (A)
- \( K_{\text{phox}} \) Phox-constant of PV-module
- \( M \) slope at open circuit point(V/A)
- \( M_{\text{PP}} \) Maximum Power Point
- \( NOCT \) Nominal Operating Cell Temperature(°C)
- \( P_{p_{\text{pk}}} \) peak power (W)
- \( R \) Resistance (Ω)
- \( R_L \) Load resistance (W)
- \( R_p \) Parallel resistance (Ω)
- \( R_{pv} \) Photovoltaik-resistance (V/A)
- \( R_{s} \) Series resistance (Ω)
- \( STC \) Standard Test Conditions (\( E_0, T_{j0} \) at AM 1.5)
- \( T \) Temperature (°C or K)
- \( T_{\text{ambN}} \) 20°C (ambient temperature for NOCT)
- \( T_{j} \) Junction-temperature (K)
- \( T_{p} \) 25°C (cell temperature at STC)
- \( V \) Voltage (V)
- \( V_{D} \) Diode-voltage (V)
- \( V_{L} \) Actual voltage at working point (V)
- \( V_{oc} \) Open circuit voltage (V)
- \( V_{p_{\text{max}}} \) Voltage at MPP (V)
- \( V_{T} \) Temperature-voltage (K)

**REFERENCES**


