PEAK-POWER AND INTERNAL SERIES RESISTANCE MEASUREMENT UNDER NATURAL AMBIENT CONDITIONS

ANDREAS WAGNER
University of Applied Sciences Dortmund, P.O.Box 10 50 18, D-44047 Dortmund, Germany,
Fax + 49 231 9112283, e-mail wagner@fh-dortmund.de

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 explicitely 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 determin 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 explicitely calculate the demanded points of the I-V-characteristic, thus beeing 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 necessery 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 conlusions 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 affilated 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_{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%)

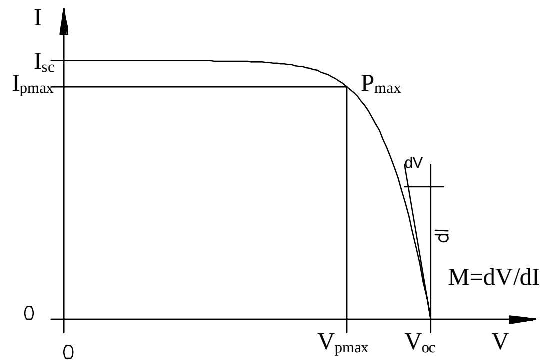

Fig. 1. Current–voltage–characteristic

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:

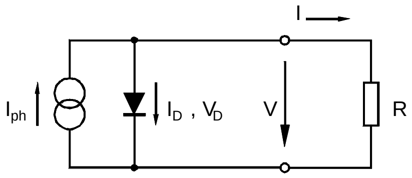

Fig.2. Ideal model.

Low approximation accuracy.

$$I = I_{ph} - I_0(e^{\frac{V}{V_T}} - 1) \tag{1}$$

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

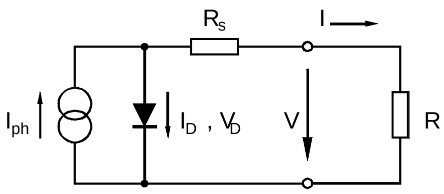

Fig. 3. Simple model

Good approximation accuracy.

$$I = I_{ph} - I_0(e^{\frac{V+IR_s}{V_T}} - 1) \tag{3}$$

$$V = V_T \ln(\frac{I_{ph} - I + I_0}{I_0}) - IR_s \tag{4}$$

Value for R_s can become negative.

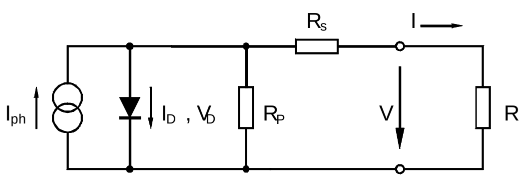

Fig. 4. Standard model

Good approximation accuracy.

$$I = I_{ph} - I_0(e^{\frac{V+IR_s}{V_T}} - 1) - \frac{V + IR_s}{R_p} \tag{5}$$

V=? explicit solution unknown.

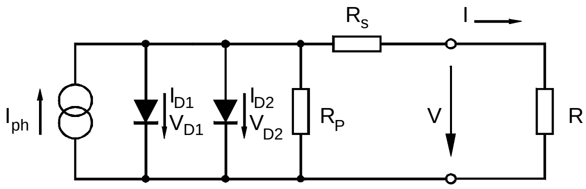

Fig. 5. Two-diodes-model

Very good approximation accuracy.

$$I = I_{ph} - I_{01}(e^{\frac{V+IR_s}{V_{T1}}} - 1) - I_{02}(e^{\frac{V+IR_s}{V_{T2}}} - 1) - \frac{V + IR_s}{R_p} \tag{6}$$

V=? explicit solution unknown.

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}

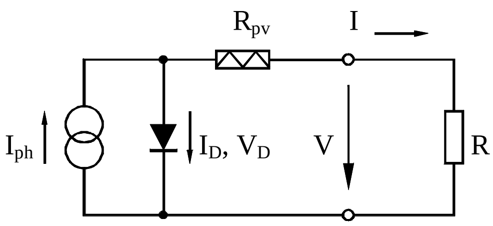

Fig. 6. Equivalent circuit diagram for the effective solar cell characteristic

Follows the effective solar cell chracteristic:

$$I = I_{ph} - I_0(e^{\frac{V+IR_{pv}}{V_T}} - 1) \tag{7}$$

Explicit version

$$V = V_T \ln(\frac{I_{ph} - I + I_0}{I_0}) - IR_{pv} \tag{8}$$

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_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 (Fig. 1)

$$M = \frac{dV}{dI}(I = 0) \tag{9}$$

then for the 4 equation parameters 5 equations are available:

$$V(I = 0) = V_{oc} \tag{10}$$

$$V(I = I_{sc}) = 0 \tag{11}$$

$$V(I = I_{p\max}) = V_{p\max} \tag{12}$$

$$\frac{d(V \cdot I)}{dI}(I = I_{p\max}) = 0 \tag{13}$$

$$\frac{dV}{dI}(I = 0) = M \tag{14}$$

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

$$R_{pv} = -M \frac{I_{sc}}{I_{p\max}} + \frac{V_{p\max}}{I_{p\max}}\left(1 - \frac{I_{sc}}{I_{p\max}}\right) \tag{15}$$

$$V_T = -(M + R_{pv}) I_{sc} \tag{16}$$

$$I_0 = I_{sc} e^{-\frac{V_{oc}}{V_T}} \tag{17}$$

$$I_{ph} = I_{sc} \tag{18}$$

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

$$M = f(I_{sc}, V_{oc}, I_{p\max}, V_{p\max}) \tag{19}$$

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).

$$M = \frac{V_{oc}}{I_{sc}}\left(k_1 \frac{I_{p\max} V_{p\max}}{I_{sc} V_{oc}} + k_2 \frac{V_{p\max}}{V_{oc}} + k_3 \frac{I_{p\max}}{I_{sc}} + k_4\right) \tag{20}$$

with the equation-constants.

$$k = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix} \tag{21}$$

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?

$$\begin{aligned} I_{sc} &= 3.65A & & & R_{pv} &= -0.624\Omega \\ V_{oc} &= 21.7A & M &= -0.222\frac{V}{A} & V_T &= 3.09V \\ I_{p\max} &= 3.15A & & & I_0 &= 3.253mA \\ V_{p\max} &= 17.5V & & & I_{ph} &= 3.65A \end{aligned} \tag{22}$$

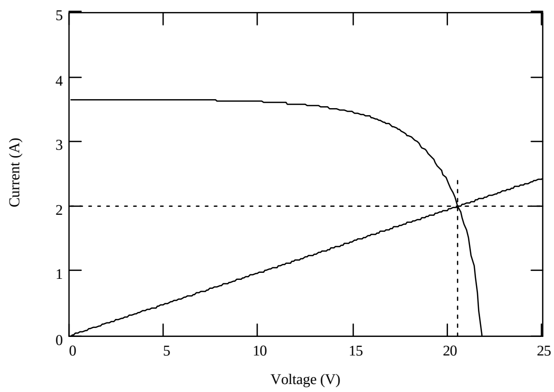

Fig. 7. Resistor as load of a solar module

with eq. (8) follows

$$\begin{aligned} V(I_L = 2A) &= 20.5V \\ R_L &= 10.25\Omega \end{aligned} \tag{23}$$

3. SERIES RESISTANCE

3.1Measuring 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 ±2°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 ΔI 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)

$$\Delta I = 0.5 \cdot I_{sc2} \tag{24}$$

- 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

$$R_s = \frac{V_2 - V_1}{I_{sc1} - I_{sc2}} \tag{27}$$

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 (ΔT<1 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.

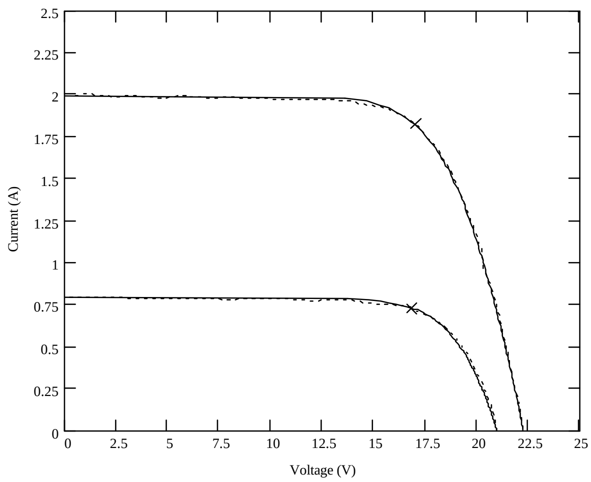

Fig. 8. Measurement for R_s-determination

Measurement 1

$$\begin{array}{lll} I_{sc1} = 1.998A & & R_{pv1} = 0.908\Omega \\ V_{oc1} = 22.235A & M = -1.652\frac{V}{A} & V_{T1} = 1.488V \\ I_{p\max 1} = 1.821A & & I_{01} = 6.442 \cdot 10^{-7} A \\ V_{p\max 1} = 16.977V & & I_{ph1} = 1.998A \end{array} \tag{28}$$

Measurement 2

$$\begin{array}{lll} I_{sc2} = 0.795A & & R_{pv2} = 0.721\Omega \\ V_{oc2} = 20.958A & M = -2.551\frac{V}{A} & V_{T2} = 1.455V \\ I_{p\max 2} = 0.730A & & I_{02} = 4.402 \cdot 10^{-7} A \\ V_{p\max 2} = 16.798V & & I_{ph2} = 0.795A \end{array} \tag{29}$$

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)

$$\Delta I = 0.5 \cdot I_{sc2} = 0.398A \tag{30}$$

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

4.1Measuring method

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

$$P_{pk} = P_{\max}(E_0, T_{j0}) \tag{35}$$

Standard Test Conditions (STC):

- Irradiance $E_0 = 1000 \dfrac{W}{m^2}$ (36)
- Solar spectrum AM 1.5 (37)
- Solar cell temperatureT_{j0} = 25 °C (= 298 K) (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

$$\begin{aligned} E_{eff} &= E \\ phox &= \frac{W}{m^2} \end{aligned} \tag{39}$$

Beyond AM 1.5 applies

$$E_{eff} = I_{sc} \cdot K_{phox} \tag{40}$$

The solar module to be measured serves as its own ”phox-meter” when its phox-constant K_{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

$$\cos(\Theta_Z) = \frac{1}{AM} \tag{41}$$

follows for AM=1.5

$$\cos(\Theta_Z) = \frac{1}{1.5} \tag{42}$$

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

Example: Dortmund (λ = –7° east. longitude, φ = 51° north. latitude) August 17. (Wagner A. 1999)

Results in Central European Summer Time

$$\begin{aligned} AM &= 1.5(am) \quad 11h\,9\min \\ AM &= 1.5(pm) \quad 16h\,4\min \end{aligned} \tag{43}$$

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.

$$K_{phox} = \frac{E_{AM\,1.5}}{I_{scAM\,1.5}} \tag{44}$$

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_{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:

$$I_{p\max 0} = I_{p\max} \frac{E_0}{E_{eff}} \tag{45}$$

$$\begin{aligned} V_{p\max 0} = &\frac{V_{p\max}}{1 + c_T(T_j - T_{j0})} \\ &+ V_T \frac{T_{j0}}{T_j} \ln\left(\frac{E_0}{E_{eff}}\right) - I_{p\max} R_{pv}\left(\frac{E_0}{E_{eff}} - 1\right) \end{aligned} \tag{46}$$

follows the peak-power

$$P_{pk} = I_{p\max 0} \cdot V_{p\max 0} \tag{47}$$

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

$$I_{sc0} = I_{sc} \frac{E_0}{E_{eff}} \qquad V_{oc0} = V_{oc} \frac{V_{p\max 0}}{V_{p\max}} \tag{48}$$

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:

typical $c_T = -0{,}0044\ K^{-1}$ (49)

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

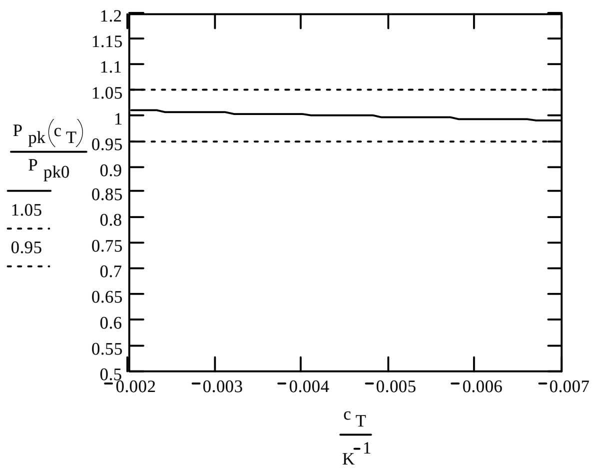

Fig. 9. Error rate due to error in temperature coefficient

Cell temperature changes depending on irradiance and ambient temperature. Often the nominal operating cell temperature is given in the data-sheet.

$NOCT = T_j(E_N, T_{ambN})$ (50)

Test conditions for the evaluation of NOCT
Nominal Operating Cell Temperature

- Irradiance $E_N = 800\frac{W}{m^2}$ (51)
- Ambient temperature $T_{ambN} = 20\ °C$ (52)

The nominal operating cell temperature 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:

typical NOCT = 48°C (53)

With the measured ambient temperature T_{amb} and NOCT the cell-temperature T_j then can approximately be calculated. (Wagner A. 1999).

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

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

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

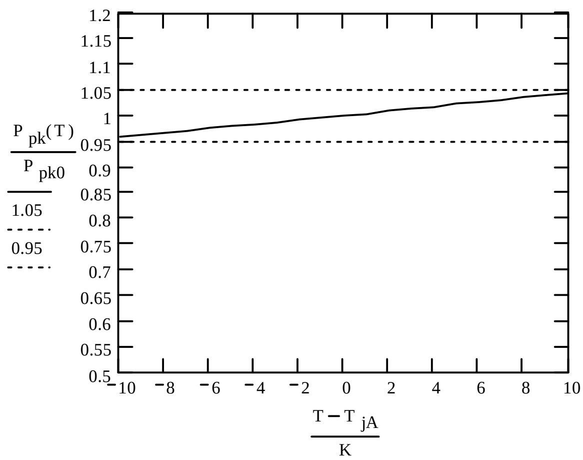

Fig. 10. Error rate due to error in cell temperature

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:

$E_{eff1} = 777$ 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

$$k = \frac{Isc_2}{Isc_1} = 0.398 \quad (56)$$

Follows

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

The following temperature has been determined:

$T_j = 294$ 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:
Measurement1

$$\begin{aligned} I_{p\max 1} &= 1.821A \\ V_{p\max 1} &= 16.977V \\ V_{T1} &= 1.488V \\ R_{pv1} &= 0.908\Omega \\ T_{j1} &= 294K \\ E_{eff1} &= 777\ phox \end{aligned} \qquad \begin{aligned} (45) &\longrightarrow I_{m1} = 2.35\,A \\ (46) &\longrightarrow V_{m1} = 16.59V \\ (47) &\longrightarrow P_{pk1} = 39W \end{aligned} \tag{59}$$

Measurement 2

$$\begin{aligned} I_{p\max 2} &= 0.730\,A \\ V_{p\max 2} &= 16.798V \\ V_{T2} &= 1.455V \\ R_{pv2} &= 0.721\Omega \\ T_{j2} &= 294K \\ E_{eff2} &= 309\ phox \end{aligned} \qquad \begin{aligned} (45) &\longrightarrow I_{m2} = 2.36\,A \\ (46) &\longrightarrow V_{m2} = 17.06V \\ (47) &\longrightarrow P_{pk2} = 40W \end{aligned} \tag{60}$$

In the present case the measurement concerns a polycrystalline module, year of production 1991.
Quality inspection: February 2000.
Data-sheet informations:
Peak-power P_{pk} = 50 W,
Tolerance ± 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_{pmax}, V_{pmax}.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 grahic 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_{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_{pmax}	Current at MPP (A)
I_{sc}	Short-circuit current (A)
K_{phox}	Phox-constant of PV-module
M	slope at open circuit point(V/A)
MPP	Maximum Power Point
NOCT	Nominal Operating Cell Temperature(°C)
P_{pk}	peak power (W) maximum power at STC
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_{ambN}	20°C (ambient temperature for NOCT)
T_j	Junction-temperature (K)
T_{j0}	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_{pmax}	Voltage at MPP (V)
V_T	Temperature-voltage (K)

REFERENCES

Duffie J.A., Beckman W.A. (1980) *Solar Engineering of Thermal Processes*. John Wiley and Sons, New York, Brisbane.

IEC 891. (1992) *Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices*.

DIN EN 60891. (1994) *Verfahren zur Umrechnung von gemessenen Strom-Spannungs-Kennlinien von photovoltaischen Bauelementen aus kristallinem Silizium auf andere Temperaturen und Einstrahlungen*.

Schulte K.M., Sommerfeld A., Wagner A. (1993) Mobiles Mess-System für PV-Stromversorgungsanlagen *Final report, research project* AG-Solar NRW, Jülich

Wagner A. (1999) *Photovoltaik Engineering. Die Methode der Effektiven Solarzellen-Kennlinie*. Springer-Verlag, Berlin, Heidelberg, New York.