PHOTOVOLTAIC MEASUREMENT RELEVANT TO THE ENERGY YIELD

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ABSTRACT

The principal task of photovoltaic measurement is to monitor the correct function of all components of a PV-system, as defects will result in losses in energy yield. Components are both the PV-generator and the peripheral equipment as well. Quality control of the peripheral equipment is approved electrical measurement engineering. But quality control of the PV-generator needs in addition the measurement of the actual sunlight. Not only the irradiance, but also the spectral distribution of the irradiance has an important influence on the efficiency of the solar cell. For this reason, special sensors for irradiance-measurement with the same spectral response as the PV-modules to be measured have to be applied.

1. ENERGY YIELD

The daily electrical energy yield W, which can be utilised by the user follows from the mean daily insolation GA, rated with the area-factor AF, which describes the change of the energy yield due to tilt and azimuth angle of the PV-generator, the peak power P_{pk} and the performance ratio PR:

$$W = GA \cdot AF \cdot P_{pk} \cdot PR \cdot \frac{m^2}{kW} \qquad (1)$$

Via the performance ratio all further losses can be desribed by their partial efficiencies η_i.

$$PR = PR_0 \cdot \prod \eta_i \qquad (2)$$

All parameters GA, AF, P_{pk}, PR_0, all η_i are directly proportional to the energy yield.

GA and PR_0 depend on weather statistics and cannot be controlled. Also the area factor AF is determined by the orientation of the PV-generator.

But the peak power P_{pk} and the effectivenesses η_i of all the other components are directly proportional to the energy yield.

2. PEAK-POWER UNDER NATURAL AMBIENT CONDITIONS

2.1 Effective Solar Cell Characteristic

Measurements of peak-power and internal series resistance under natural ambient conditions need mathematical corrections of the measured I-V-characteristic, considering irradiance and cell temperature [7]. The purpose of I-V-characteristic approximation by means of equivalent circuit diagrams lies in the explicit calculability of matching problems. 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" [6] meets all three demanded options, as it has the same approximation accuracy as the two-diodes-model.

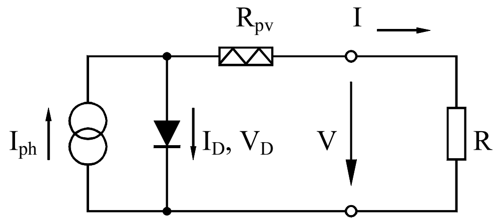

Fig. 1 Equivalent circuit diagram for the Effective Solar Cell Characteristic

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 is desribed later. Follows the effective solar cell characteristic:

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

Explicit version

$$V = V_T \ln(\frac{I_{ph} - I + I_0}{I_0}) - I R_{pv} \qquad (4)$$

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,

$$M = \frac{dV}{dI}(I = 0) \qquad (5)$$

then for the 4 equation parameters 5 equations are available. The following in general valid approximate function for the slope M could be derived [6].

$$M = \frac{V_{oc}}{I_{sc}}(k_1 \frac{I_{p\max} V_{p\max}}{I_{sc} V_{oc}} + k_2 \frac{V_{p\max}}{V_{oc}} + + k_3 \frac{I_{p\max}}{I_{sc}} + k_4) \qquad (6)$$

with the equation-constants

$$k = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix} \qquad (7)$$

Important notice: these equation-constants are independent of material properties of the solar cell.

Using this nonlinear system of simultaneous equations the equation parameters can be determined [6]:

$$R_{pv} = -M \frac{I_{sc}}{I_{p\max}} + \frac{V_{p\max}}{I_{p\max}}(1 - \frac{I_{sc}}{I_{p\max}}) \qquad (8)$$

$$V_T = -(M + R_{pv}) I_{sc} \qquad (9)$$

$$I_0 = I_{sc} e^{\frac{-V_{oc}}{V_T}} \qquad (10)$$

$$I_{ph} = I_{sc} \qquad (11)$$

Example 1: Monocrystalline PV-Module BP585F:

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

$$I_{sc} = 1.015\,A \quad V_{oc} = 20.508\,A \quad I_{p\max} = 0.951\,A \quad V_{p\max} = 17.002\,V \quad M = -1.535\frac{V}{A} \quad R_{pv} = 0.431\,\Omega \quad V_T = 1.12\,V \quad I_0 = 1.142 \cdot 10^{-8}\,A \quad I_{ph} = 1.015\,A \qquad (12)$$

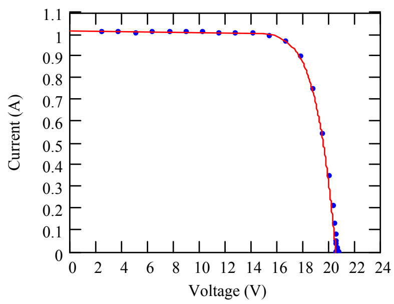

Fig.2 IV-curve approximation of a crystalline PV-module

Example 2: Amorphous PV-module Solarex MSX 40:

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

$$I_{sc} = 2.874\,A \quad V_{oc} = 22.662\,A \quad I_{p\max} = 2.099\,A \quad V_{p\max} = 14.653\,V \quad M = -2.454\frac{V}{A} \quad R_{pv} = 0.906\ \Omega \quad V_T = 4.804\ V \quad I_0 = 0.026\ A \quad I_{ph} = 2.874\ A \qquad (13)$$

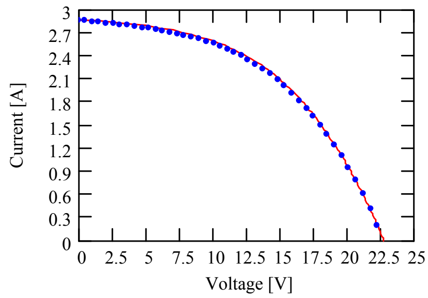

Fig.3 IV-curve approximation of an amorphous PV-module

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

2.2 Peak Power Measurement

Peak power is the maximum power under standard test conditions STC, [5].

$$P_{pk} = P_{\max}(E_0, T_{j0}) \qquad (14)$$

Standard Test Conditions (STC):

Irradiance $E_0 = 1000 \frac{W}{m^2}$ (15)

Solar spectrum AM 1.5 (16)

Solar cell temperature $T_{jo} = 25\ °C = 298\ K$ (17)

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 [7].

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 sensitivity of the human eye, it is proposed here to describe the spectral sensitivity 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

$$E_{eff} = E \qquad phox = \frac{W}{m^2} \qquad (18)$$

Beyond AM 1.5 applies

$$E_{eff} = I_{sc} \cdot K_{phox} \tag{19}$$

The phox-constant for special sensors can be measured at AM 1.5-conditions at a clear day under natural ambient conditions. All further calculations will refer to the "effective irradiance" E_{eff}, measured in phox.

With the cell-temperature T_j and the temperature coefficient c_T of power, the peak-power now can be calculated [7]. Correction to STC:

$$I_{p\max 0} = I_{p\max} \frac{E_0}{E_{eff}} \tag{20}$$

$$V_{p\max 0} = \frac{V_{p\max}}{1 + c_T(T_j - T_{j0})} + V_T \frac{T_{j0}}{T_j} \ln(\frac{E_0}{E_{eff}}) - I_{p\max} R_{pv} (\frac{E_0}{E_{eff}} - 1) \tag{21}$$

follows the peak power

$$P_{pk} = I_{p\max 0} \cdot V_{p\max 0} \tag{22}$$

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

$$I_{sc0} = I_{sc} \frac{E_0}{E_{eff}} \qquad V_{oc0} = V_{oc} \frac{V_{p\max 0}}{V_{p\max}} \tag{23}$$

For the application of formula (23) 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:

$$\text{typical} \quad c_T = -0.0044\,K^{-1} \tag{24}$$

The cell temperature will be in balance with the temperature of a sensor for the effective irradiance, which is positioned under the same orientation as the PV-module to be measured. So the cell-temperature can be obtained by a Pt1000 at the backside of the sensor.

The accuracy of this peak-power correction is 5%.

Fig.4 Peak-Power Measuring Instrument PVPM 6020C Iserlohn, Germany, **www.pv-engineering.de**

3. EFFECTIVE IRRADIANCE

Not only the irradiance, but also the spectral distribution of the irradiance has an important influence on the efficiency of the solar cell. So the use of a special sensor [1] for the measurement of the effective irradiance is significant for the new method of peak-power-measurement.

The following diagrams show the systematic error in peak-power measurement, which results, if a pyranometer is used for the measurement of the irradiance instead of an adequate sensor, such as SENSOL®-sensors [2].

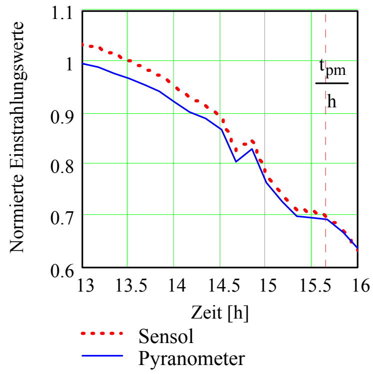

Fig. 5 Measurements by ISET Kassel, Germany

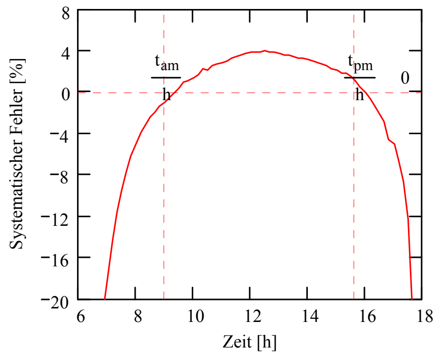

Fig.6 Systematic error for pyranometer

For the measurement of the effective irradiance SENSOL®-sensors are applied.

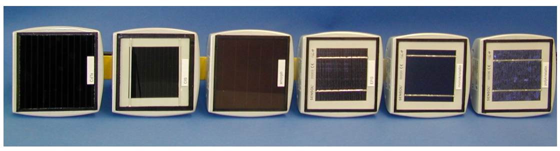

Fig.7. Several SENSOL® for several technolgies.

4. INTERNAL SERIES RESISTANCE DETERMINED OF ONLY ONE IV-CURVE

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

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 [4]

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 ΔI. Here:

$$\Delta I = 0.5 \cdot I_{sc2} \tag{25}$$

Determination of the working points V_1 and V_2 with (4)

$$V_1 = V(I_{sc1} - \Delta I, R_{pv1}, V_{T1}, I_{01}, I_{ph1}) \tag{26}$$

$$V_2 = V(I_{sc2} - \Delta I, R_{pv2}, V_{T2}, I_{02}, I_{ph2}) \tag{27}$$

Calculation of the series resistance

$$R_s = \frac{V_2 - V_1}{I_{sc1} - I_{sc2}} \tag{28}$$

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

Characteristic 1: Measurement

$$I_{sc1} \quad V_{oc1} \quad I_{p\max 1} \quad V_{p\max 1} \tag{29}$$

Characteristic 2: Simulation

$$FF = \frac{I_{p\max 1} \cdot V_{p\max 1}}{I_{sc1} \cdot V_{oc1}}$$

$$f_i = \begin{cases} FF \ \ if \ \ FF \geq 0.7 \\ 2.2 \cdot 10^{-9} \cdot e^{28 \cdot FF} \ \ otherwise \end{cases} \tag{30}$$

$$f_v = 1 \longrightarrow no\ change\ in\ Voltage \tag{31}$$

FF is the same for both characteristcs, so:

$$\begin{matrix} I_{sc2} = f_i \cdot I_{sc1} & V_{oc2} = V_{oc1} \\ I_{p\max 2} = f_i \cdot I_{p\max 1} & V_{p\max 2} = V_{p\max 1} \end{matrix} \tag{32}$$

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.

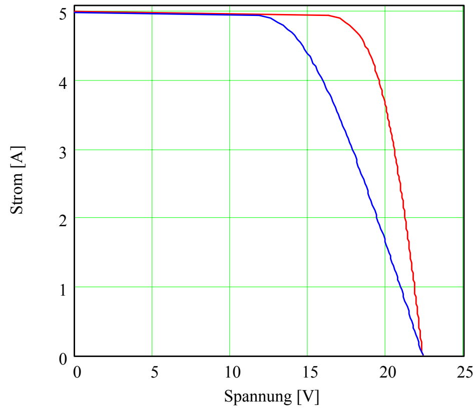

Fig.8 BP 585F with(left) and without(right) R_s-manipulation

Measurement A without manipulation:

$$\left.\begin{matrix} I_{scA} = 5\,A & V_{ocA} = 22.3\,V \\ I_{p\max A} = 4.72\,A & V_{p\max A} = 18\,V \end{matrix}\right\} R_{sA} = 0.4\,\Omega \tag{33}$$

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

$$\left.\begin{matrix} I_{scB} = 5\,A & V_{ocB} = 22.3\,V \\ I_{p\max A} = 4.51\,A & V_{p\max A} = 14.56\,V \end{matrix}\right\} R_{sA} = 1.3\,\Omega \tag{34}$$

The manipulation can be detected here.

5. CONCLUSIONS

By measurement of only one present IV-characteristic under natural ambient conditions [7] in conjunction with the measurement of the effective irradiance [1] and temperature, the complete information about P_{pk},, R_s and also parallel resistance R_p [6] is available.

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