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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Photovoltaic devices –
Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices

Dispositifs photovoltaïques –
Partie 1-1: Mesurage des caractéristiques courant-tension des dispositifs photovoltaïques (PV) multijonctions

IEC 60904-1-1:2017-05(en-fr)

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PHOTOVOLTAIC DEVICES –

Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices

FOREWORD

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International Standard IEC 60904-1-1 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
82/1254/FDIS	82/1272/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

PHOTOVOLTAIC DEVICES –

Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices

1 Scope

This part of IEC 60904 describes procedures for the measurement of the current-voltage characteristics of multi-junction photovoltaic devices in natural or simulated sunlight. It is applicable to single PV cells, sub-assemblies of such cells or entire PV modules. It is principally intended for non-concentrating devices, but parts may be applicable also to concentrating multi-junction PV devices. An essential prerequisite is the spectral responsivity of the multi-junction devices, whose measurement is covered by IEC 60904-8-1.

The requirements for measurement of current-voltage characteristics of single-junction PV devices are covered by IEC 60904-1 whereas this document describes the additional requirements for the measurement of current-voltage characteristics of multi-junction PV devices.

This document may be applicable to PV devices designed for use under concentrated irradiation if they are measured without the optics for concentration and irradiated using direct normal irradiance and a mismatch correction with respect to a direct normal reference spectral irradiance distribution is performed. The reference spectral irradiance distribution is provided in IEC 60904-3

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60891, *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for photovoltaic reference devices*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC 60904-4, *Photovoltaic devices – Part 4: Reference solar devices – Procedures for establishing calibration traceability*

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-8, *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

IEC 60904-8-1, *Photovoltaic devices – Part 8-1: Measurement of spectral responsivity of multi-junction photovoltaic (PV) devices*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following apply.

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3.1
current limiting junction
junction in a multi-junction photovoltaic device in which under given illumination conditions the lowest photovoltaic current is generated

4 General considerations

The procedure for measurement of the current-voltage characteristics of single-junction PV devices is described in detail in IEC 60904-1. The procedure for measurement of the current-voltage characteristics of a multi-junction PV device is based on the same basic principles, but requires some additional elements, which are described herein.

This document describes the additional considerations, requirements and procedures for the measurement of the current-voltage characteristics of multi-junction PV devices based on the measurement principles of single-junction PV devices.

Therefore, the provisions in IEC 60904-1 are also valid for the measurement of multi-junction PV devices except where explicitly amended by this document.

Multi-junction PV devices consist of two or more series-connected junctions. In general it is only possible to determine the current-voltage characteristics of the entire device. However, it may be useful to quantify the photovoltaic current associated with each individual junction and excessive variation of current with voltage in the current-voltage characteristics between the short-circuit and maximum-power point that may indicate shunting of each junction. To understand the performance of a multi-junction device under different spectra it is helpful to characterize each junction within it.

Luminescent coupling may be present and influence the measurements. For example, light emitted from a GaInP cell may be absorbed and generate photovoltaic current in an underlying GaAs junction. Similarly, a photon emitted by a GaAs cell may be absorbed and generate photovoltaic current in an underlying Ge junction. For relatively high efficiency cells, the coupling between the cells in this way can cause non-negligible changes in measured current under some conditions. For details see bibliography.

For multi-junction PV devices which provide separate connections to each junction, the measurement of current-voltage characteristics of each single-junction is possible and follows the procedure for single-junction devices (IEC 60904-1) using the appropriate connections.

5 General measurement requirements

The general requirements for the measurement of current-voltage characteristics of multi-junction PV devices are identical to those for single-junction devices given in IEC 60904-1.

Due to the series-connection of the junctions in a multi-junction device the measured current-voltage characteristics are a complex function of the photovoltaic currents generated in each of the junctions. Therefore the measurement conditions for multi-junction devices should strive to generate photovoltaic currents in each junction similar to those which would be generated in that junction under the reference spectral irradiance distribution. In general this can be achieved with a test spectral irradiance distribution close to the reference spectral irradiance distribution such as provided by natural sunlight under suitable conditions or with a solar simulator whose spectral irradiance is adjustable. However, measurement conditions will never be perfect and deviate from the reference conditions. This document sets limits to the permissible deviations for obtaining valid measurements. Smaller deviations are preferable, but may not be achievable in all cases. In any case the deviations of the measurement conditions from the reference conditions shall be accounted for in the analysis of measurement uncertainty.

The junction with the lowest generated photovoltaic current is referred to as the current-limiting junction. In any case the measurement conditions should be chosen such that the current-limiting junction under the test spectral irradiance distribution is the same as the one under the reference spectral irradiance distribution.

Additionally, but optionally, for a more complete characterization of the multi-junction device, measurements can be taken with each junction serving as the current-limiting junction. The resulting I-V curves are used to identify the photovoltaic current and effective shunting of that junction. For details see bibliography (Meusel *et al.,* 2002).

For these additional optional measurements a simulator with an adjustable spectral irradiance distribution is preferable. However, natural sunlight is in principle also suitable (using the variation of the spectral irradiance with air mass), but might be impracticable.

6 Apparatus

6.1 General requirements for irradiance

6.1.1 General

Solar simulators used to measure multi-junction devices shall be class AAA according to IEC 60904-9. For measurements made using natural sunlight the conditions should fulfil the same requirements. The spectral responsivity of the multi-junction devices might cover a wider wavelength range than that defined in IEC 60904-9 for determination of spectral match classification of the solar simulator. In that case add additional wavelength bands of 200 nm each until the entire wavelength range of spectral responsivity of the multi-junction device is covered. The simulator should fulfil for all wavelength bands the respective criterion for class A for spectral match as defined in IEC 60904-9.

The relative spectral irradiance of the test spectral irradiance distribution shall be measured with a spectroradiometer over the entire wavelength range of spectral responsivity of the multi-junction device. For measurements under natural sunlight the spectral irradiance shall be measured simultaneously with the measurements of the current-voltage characteristics of the test device. For simulated sunlight the spectral irradiance may also be measured before or after the measurement of the current-voltage characteristics. In this case the stability in time of the spectral irradiance of the simulated sunlight shall be considered in the uncertainty analysis. For pulsed solar simulators not only the repeatability from pulse to pulse, but also the stability of the spectral irradiance during a pulse and the spatial uniformity of spectral irradiance over the test plane shall be considered.

6.1.2 Solar simulator with adjustable spectral irradiance

A solar simulator with adjustable spectral irradiance is preferred for the measurements of multi-junction devices. Such simulators are normally multi-source simulators or equipped with variable optical filters. In a multi-source simulator there should be at least one source for each junction in the multi-junction PV device, contributing mainly in the wavelength range where the respective junction responds. Alternatively, for simulators with a smaller number of sources (including single-source), the spectral irradiance can be changed by placing appropriate optical filters between the light source and the device under test. It might also be possible to vary the spectral irradiance by setting different power levels of single-source simulators.

6.1.3 Solar simulator with fixed spectral irradiance

Single-source solar simulators normally have a fixed spectral irradiance, but their total irradiance intensity can often be varied. However, the spectral irradiance might change with total irradiance intensity; therefore the former should be determined under settings identical to those used for the current-voltage measurement. Such simulators are only suitable for the measurement of multi-junction devices if they fulfil the requirements of 7.3.

6.1.4 Natural sunlight

Natural sunlight offers a restricted range of total and spectral irradiance. Variations depend on air mass and atmospheric conditions occurring either at different times during one day or at days in different seasons. However, in practical terms it will be difficult to systematically use these variations for the measurements. Nevertheless, natural sunlight under suitable conditions offers a spectral irradiance distribution closely matching the reference spectral irradiance distribution. When the requirements of 7.3 are met, natural sunlight is suitable for the measurement of multi-junction devices.

6.2 Reference devices

Reference devices fulfilling the requirements of IEC 60904-2 and 60904-4 shall be selected according to one of the following three possibilities:

a) *n* component reference devices each of which is matched in spectral responsivity to the respective junction in the *n*-junction PV device under test. The spectral responsivity is considered matched when the spectral mismatch correction (between the component reference device and the respective junction for the test spectral irradiance distribution and the reference spectral irradiance distribution) determined according to IEC 60904-7 is within ±1 %. This is the preferred choice when using adjustable solar simulators, as it makes the adjustment convenient and reduces the uncertainties introduced by the measurement of the spectral irradiance;

b) *n* component reference devices each of which approximates the spectral responsivity of the respective junction in the *n*-junction PV device under test. The spectral responsivity is considered approximated when the spectral mismatch correction (between the component reference device and the respective junction for the test spectral irradiance distribution and the reference spectral irradiance distribution) determined according to IEC 60904-7 is within ±5 %. This is the preferred choice in particular when using adjustable solar simulators, when matched component reference devices (see a) above) are not available. It preserves convenience at the expense of increased measurement uncertainty due to determination of the residual spectral mismatch;

c) a broadband reference device (such as a crystalline-Silicon) is the preferred choice for measurements under natural sunlight. In this case the spectral mismatch correction is small and the spectral irradiance can be determined with sufficient accuracy to limit contribution to measurement uncertainty.

While matched reference devices are preferable they might not be readily available, in particular for new or emerging multi-junction technologies.

Component reference devices can be made from standard reference devices (e.g. crystalline-Silicon) by addition of suitable optical filters to give a combined spectral responsivity matching the junctions in the multi-junction device. Alternatively such component reference devices could be of the same technology as the multi-junction device, but with the other junctions electrically disabled or with special electrical connections for each junction. In any case the stability of the component reference device has to be considered and appropriate handling and stabilisation procedures put into place.

Broadband reference devices have the advantage of being readily available, generally with a calibration uncertainty lower than that for component reference devices.

For any choice of reference device(s) a detailed measurement uncertainty calculation for the final results needs to be made, considering the calibration uncertainty of the reference device(s), the drift of the calibration value as well as the uncertainty in determining the measurement conditions with these reference devices.

Both broadband and component reference devices are single-junction devices. The use of multi-junction reference device (for example a multi-junction reference module) is not possible, as different measurement conditions might yield the same compound output of such a device. Therefore, adjusting the measurement conditions to yield the calibration value of such a multi-junction reference device does not guarantee the correct measurement conditions for the device under test.

7 Measurement conditions

7.1 General considerations

The measurement conditions for current-voltage characteristics of multi-junction devices require more attention than for single-junction devices because the measurement results for multi-junction devices are more prone to effects due to measurement conditions deviating from the reference conditions.

The parameters calculated as described below shall adhere to the given limitations, which define the permissible measurement conditions. The calculated parameters shall also be reported with the measurement results as indicated in Clause 10.

A proper selection of measurement conditions avoids or minimizes the magnitude of the correction that shall be applied to the measured current-voltage characteristics (see Clause 9). In any case a detailed analysis of measurement uncertainties is required.

7.2 Parameters

The following quantities shall be calculated based on the measured spectral responsivity (IEC 60904-8 and IEC 60904-8-1) of each junction in the multi-junction device, on the spectral responsivity of the reference device(s) and on the test and reference spectra:

- the matching of the effective irradiance to the reference irradiance:

$$Z_{\mathrm{i}} = \frac{G_{\mathrm{ref}}}{G_{\mathrm{i,meas}} MM_{\mathrm{i}}} \tag{1}$$

where

i is the junction index;

Z_{i} is a matching factor for the *i*-th junction;

G_{ref} is the reference irradiance;

$G_{i,meas}$ is the irradiance as measured by the *i*-th reference device (in case of a single reference device this quantity is equal for each junction);

MM_i is the mismatch factor for the *i*-th junction with respect to the *i*-th reference device, the test and the reference spectral irradiance distributions, calculated according to IEC 60904-7.

Z shall be calculated for all junctions. This quantity essentially represents the match between the effective irradiance (IEC 60904-7) during measurement and the reference spectral irradiance distribution, considering spectral mismatch.

Furthermore the following quantities might be useful, but their calculation is optional:

- the current generated in each junction

$$j_i = A_i \int SR_i(\lambda) G(\lambda) d\lambda \tag{2}$$

where

j_i is the current of the *i*-th junction;

A_i is the active area of the junction;

SR_i is its absolute spectral responsivity;

G is the spectral irradiance (for both the reference irradiance G_{ref} as well as the irradiance G_{meas} under which the current-voltage characteristic was measured);

λ is the wavelength.

- the current-limiting junction

$$j_{lim} = \min(j_i) \tag{3}$$

- the current balance between junctions

$$Bal_{ij,i\neq j} = \frac{j_i}{j_j} \tag{4}$$

The calculation in formula (2) requires in general the absolute spectral responsivity. However, if the spectral responsivity of all junctions is known on the same relative scale, the calculations are nevertheless meaningful.

7.3 Measurement conditions

The following conditions shall be fulfilled during the measurements of current-voltage characteristics:

- the matching factor Z_i for all junctions is within 1,00 ± 0,03. The smaller the deviation from unity, the smaller the measurement uncertainty and the higher the quality of the measurement. Therefore a matching of 1,00 ± 0,01 should be targeted but might not be achievable in all cases.

Furthermore the following conditions should be met. Their determination is useful but not obligatory.

- the current-limiting junction under the test spectral irradiance distribution is the same as under the reference spectral irradiance distribution
- the current balance Bal_{ij} between all combinations of junctions agrees to within ±5 % under the test spectral irradiance distribution with respect to the reference spectral irradiance distribution. Better agreement is desirable for reducing measurement uncertainty.