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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Photovoltaic devices –
Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices

Dispositifs photovoltaïques –
Partie 7: Calcul de la correction de désadaptation des réponses spectrales dans les mesures de dispositifs photovoltaïques

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PHOTOVOLTAIC DEVICES –

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FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60904-7 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This fourth edition cancels and replaces the third edition published in 2008. It constitutes a technical revision.

The main technical changes with respect to the previous edition are as follows:

- For better compatibility and less redundancy, the clause "Determination of test spectrum" refers to IEC 60904-9.
- The spectral mismatch factor is called SMM instead of MM to enable differentiation to the angular mismatch factor AMM and spectral angular mismatch factor $SAMM$.
- Formulae for the derivation and application of the spectral mismatch factor SMM are added.
- Links to new standards are given, e.g. concerning multi-junction devices.

- Corrected wording (responsivity instead of response and irradiance instead of intensity).

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

FDIS	Report on voting
82/1590/FDIS	82/1605/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 of 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 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices

1 Scope

This part of IEC 60904 describes the procedure for correcting the spectral mismatch error introduced in the testing of a photovoltaic device, caused by the mismatch between the test spectrum and the reference spectrum (e.g. AM1.5 spectrum) and by the mismatch between the spectral responsivities (SR) of the reference device and of the device under test and therewith reduce the systematic uncertainty. This procedure is valid for single-junction devices but the principle may be extended to cover multi-junction devices.

The purpose of this document is to give guidelines for the correction of the spectral mismatch error, should there be a spectral mismatch between the test spectrum and the reference spectrum as well as between the reference device SR and the device under test SR. The calculated spectral mismatch correction is only valid for the specific combination of test and reference devices measured with a particular test spectrum.

Since a PV device has a wavelength-dependent spectral responsivity, its performance is significantly affected by the spectral distribution of the incident radiation, which in natural sunlight varies with several factors such as location, weather, time of year, time of day, orientation of the receiving surface, etc., and with a solar simulator varies with its type and conditions. If the irradiance is measured with a thermopile-type radiometer (that is not spectrally selective) or with a PV reference device (IEC 60904-2), the spectral irradiance distribution of the incoming light must be known to make the necessary corrections to obtain the performance of the PV device under the reference spectral irradiance distribution defined in IEC 60904-3.

If a reference PV device or a thermopile type detector is used to measure the irradiance, then, following the procedure given in this document, it is possible to calculate the spectral mismatch correction necessary to obtain the short-circuit current of the device under test under the reference spectral irradiance distribution in IEC 60904-3 or any other reference spectrum. If the reference PV device has the same relative spectral responsivity as the device under test then the reference device automatically takes into account deviations of the measured spectral irradiance distribution from the reference spectral irradiance distribution, and no further correction of spectral mismatch errors is necessary. In this case, location and weather conditions are not critical when the reference device method is used for performance measurements under natural sunlight. Also, for identical relative SRs, the spectral classification of the simulator is not critical for measurements with solar simulators.

If the performance of a PV device is measured using a known spectral irradiance distribution, its short-circuit current at any other spectral irradiance distribution can be computed using the spectral responsivity of the PV device under test.

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 60904-1-1, *Photovoltaic devices – Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices*

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 60904-8, *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*

ISO 9288:1989, *Thermal insulation – Heat transfer by radiation – Physical quantities and definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and ISO 9288 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

NOTE The index e for the energetic quantities is omitted, as in this document the quantities need not be distinguished from photometric quantities. Thus, for the quantity irradiance the quantity symbol E instead of the quantity symbol E_e is used.

The index λ that denotes that the irradiance is differentiated with respect to the wavelength λ and not to the frequency ν to obtain the spectral irradiance $E_\lambda(\lambda)$ is mostly omitted for clarity. Therefore, the spectral irradiance is referred to herein as $E(\lambda)$.

4 Description of method

For many PV devices, the shape of the I-V characteristic depends on the short-circuit current and the device temperature, but not on the spectrum used to generate the short-circuit current. For these devices, the correction of spectrum mismatch or spectral responsivity mismatch is possible using the following procedure. For other devices, a measurement of the I-V characteristic shall be done using a light source with the appropriate spectrum.

A correction is not necessary if either the test spectrum is identical to the reference spectrum (see IEC 60904-3) or if the device under test's relative spectral responsivity is identical to the reference device relative spectral responsivity. In this case, the reading as obtained from the reference device specifies which irradiance at the reference spectrum will generate the same short-circuit current in the device under test as the test spectrum.

If there is a mismatch between spectra (spectrum mismatch) as well as spectral responsivities (spectral responsivity mismatch) then a mismatch correction should be calculated. As the test spectrum and the spectral responsivities always have an assigned measurement uncertainty, for the calculation of the total uncertainty the uncertainty of spectral mismatch shall be always taken into account.

When a mismatch in spectra and/or spectral responsivities exists, the reading of the reference device (see IEC 60904-2) does not give the irradiance of the test spectrum that would generate the same short-circuit current for the device under test as the reference spectrum. Therefore, one shall determine the effective irradiance of the test spectrum, E_{eff} that generates the same short-circuit current in the device under test as generated by the reference spectrum.

$$E_{\mathrm{eff}} = SMM \times E_{\mathrm{meas}} \tag{1}$$

where E_{meas} is the irradiance as measured by the reference device with its specific spectral responsivity $s_{\mathrm{ref}}(\lambda)$ before applying spectral mismatch corrections and SMM is the spectral mismatch factor as determined in Clause 7.

For a measurement to be referred to the reference spectral irradiance, two correction methods are possible:

a) If possible, adjust the measured test spectrum irradiance so that the effective irradiance as determined by formula (1) equals the reference irradiance E_{ref} (e.g. 1 000 W/m2 for STC, as defined in IEC TS 61836). That is to say that the solar simulator's irradiance as measured by the reference device using its calibration value before applying spectral mismatch correction given for the reference spectrum has to be set to

$$E_{\mathrm{meas}} = E_{\mathrm{ref}} \,/\, SMM \tag{2}$$

Thus, the inverse mismatch factor $1/SMM$ gives the degree by which the solar simulator's irradiance has to be adjusted. Now, the solar simulator spectrum at this irradiance with its actual measured test spectrum generates the same short-circuit current for the device under test as would be obtained under the reference spectrum. If the adjustment is done without using the feedback of the reference device (e.g. using a control dial), the adjusted value should be checked using a reference device. Thereafter, proceed to measure the I-V characteristic as per IEC 60904-1.

b) Otherwise, measure the I-V characteristic using the measured spectral irradiance. Determine the effective irradiance at the reference spectrum using formula (1). Then translate the I-V characteristic to the reference irradiance using IEC 60891 with the effective irradiance determined from formula (1).

Method a) is preferred for simulated sunlight, as the actual measurement is performed at the correct reference irradiance, minimising non-linearity errors of the device under test and errors arising from the I-V curve translation. Method b) is usually chosen for measurements under natural sunlight, as the spectral irradiance of sunlight cannot be easily adjusted.

5 Determination of spectral responsivity

5.1 If not available, the relative spectral responsivity of the device under test and the reference device shall be measured according to IEC 60904-8 for single-junction devices and IEC 60904-8-1 for multi-junction devices under test.

5.2 Take care not to use the differential spectral responsivity, but the spectral responsivity, that can be calculated using differential spectral responsivities at different bias level (see IEC 60904-8).

6 Determination of test spectrum

The relative spectral irradiance distribution of the radiation source shall be measured according to IEC 60904-9. This shall be done for simulated as well as natural sunlight.

7 Determination of the spectral mismatch factor

7.1 General

Determine the spectral mismatch factor from **:**

$$SMM = \frac{\int E_{\text{ref}}(\lambda) s_{\text{ref}}(\lambda)\, d\lambda \int E_{\text{meas}}(\lambda)\, s_{\text{DUT}}(\lambda)\, d\lambda}{\int E_{\text{meas}}(\lambda) s_{\text{ref}}(\lambda)\, d\lambda \int E_{\text{ref}}(\lambda)\, s_{\text{DUT}}(\lambda)\, d\lambda} \tag{3}$$

where

$E_{\text{ref}}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength λ, of the reference spectral irradiance distribution (reference spectrum), for example as given in IEC 60904-3;

$E_{\text{meas}}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength λ, of the spectral irradiance distribution of the incoming light at the time of measurement (test spectrum);

$s_{\text{ref}}(\lambda)$ is the spectral responsivity of the reference PV device at reference conditions;

$s_{\text{DUT}}(\lambda)$ is the spectral responsivity of the device under test at reference conditions.

All integrals shall be performed in the entire spectral range where the respective quantities are not zero. The irradiance distribution shall be known over the entire combined spectral range of sensitivity of the device under test and the reference PV device.

The spectral irradiance distributions and the spectral responsivities can be given on an absolute or relative scale.

If the relative test spectrum would be identical to relative reference spectrum, then the *SMM* is 1 and spectral mismatch corrections can be neglected, even if the spectral responsivities of the devices differ. However, considering that the test spectrum as a physical quantity has a measurement uncertainty assigned to it that is not zero, the *SMM* will still have a measurement uncertainty contribution different to zero. Thus, the *SMM* factor cannot be neglected when considering its measurement uncertainty contribution, though the value of the factor is 1.

If the relative spectral responsivity of the device under test would be identical to the relative spectral responsivity of the reference device, then the SMM is 1, even if the relative spectral irradiance distributions differ (perfectly matched reference device). Considering that both spectral responsivities have a measurement uncertainty that is not zero, the SMM will still have a measurement uncertainty contribution different to zero. Thus, the SMM factor cannot be neglected when considering its measurement uncertainty contribution, though the value of the factor is 1.

Due to the irregular shape of the reference and measured spectra, spectral responsivities should be interpolated to the wavelength points of the spectral irradiance measurements, not vice versa.

Formula (3) is valid for single-junction devices, but may be used for multi-junction devices. For multi-junction devices, the calculation shall be performed for each junction in the device, using its spectral responsivity including the spectral filtering caused by the junctions above the junction under consideration. The test report should specify the spectral mismatch factors and the relative current generation of the individual junctions. For multi-junction devices, refer to IEC 60904-1-1 (I-V) and IEC 60904-8-1 (SR).

The spectral responsivities used shall be valid at the level of target irradiance for which the SMM factor applies because for non-linear devices they may vary with the level of irradiance.

Derivation of SMM

In the case that absolute spectral irradiances and absolute spectral responsivities are used for the analysis, Formula (3) can be interpreted as:

$$SMM = \frac{I_{\mathrm{ref},E_{\mathrm{ref}}}\, I_{\mathrm{DUT},E_{\mathrm{meas}}}}{I_{\mathrm{ref},E_{\mathrm{meas}}}\, I_{\mathrm{DUT},E_{\mathrm{ref}}}} \qquad (4)$$

where

$I_{\mathrm{DUT},\,E_{\mathrm{ref}}}$	is the short-circuit current of the device under test that would be obtained under the reference spectrum $E_{\mathrm{ref}}(\lambda)$;
$I_{\mathrm{ref},\,E_{\mathrm{ref}}}$	is the short-circuit current of the reference device that would be obtained under the reference spectrum $E_{\mathrm{ref}}(\lambda)$;
$I_{\mathrm{DUT},\,E_{\mathrm{meas}}}$	is the short-circuit current of the device under test under the measured test spectrum $E_{\mathrm{meas}}(\lambda)$;
$I_{\mathrm{ref},\,E_{\mathrm{meas}}}$	is the short-circuit current of the reference device under the measured test spectrum $E_{\mathrm{meas}}(\lambda)$

because $I_{\mathrm{sc}} \propto \int E_{\lambda}(\lambda)\, s(\lambda)\, d\lambda$.

Using these quantities, one can write according to the definition of the responsivity:

$$s_{\mathrm{DUT}} = \underbrace{\frac{I_{\mathrm{DUT},\,E_{\mathrm{ref}}}}{E_{\mathrm{ref}}}}_{\text{What you want to know}} = s_{\mathrm{ref}} \cdot \frac{I_{\mathrm{DUT},\,E_{\mathrm{ref}}}}{I_{\mathrm{ref},\,E_{\mathrm{ref}}}} = s_{\mathrm{ref}} \cdot \frac{I_{\mathrm{DUT},\,E_{\mathrm{ref}}}}{I_{\mathrm{ref},\,E_{\mathrm{ref}}}} \cdot \underbrace{\frac{I_{\mathrm{ref},\,E_{\mathrm{meas}}}}{I_{\mathrm{DUT},\,E_{\mathrm{meas}}}} \cdot \frac{I_{\mathrm{DUT},\,E_{\mathrm{meas}}}}{I_{\mathrm{ref},\,E_{\mathrm{meas}}}}}_{1} = s_{\mathrm{ref}} \cdot \frac{1}{SMM} \cdot \underbrace{\frac{I_{\mathrm{DUT},\,E_{\mathrm{meas}}}}{I_{\mathrm{ref},\,E_{\mathrm{meas}}}}}_{\text{What you measure}} \qquad (5)$$