IEC 60904-9

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Photovoltaic devices –
Part 9: Classification of solar simulator characteristics

Dispositifs photovoltaïques –
Partie 9: Classification des caractéristiques des simulateurs solaires

IEC 60904-9:2020-09(en-fr)

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FOREWORD

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International Standard IEC 60904-9 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This third edition cancels and replaces the second edition issued in 2007. It constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- Changed title;
- Added spectral match classification in an extended wavelength range;
- Introduction of new A+ class;
- Definition of additional parameters for spectral irradiance evaluation;
- Added apparatus sections for spectral irradiance measurement and spatial uniformity measurement;

- Revised procedure for spectral match classification (minimum 4 measurement locations);
- Revised measurement procedure for spatial uniformity of irradiance;
- Added informative Annex A for sensitivity analysis of spectral mismatch error related to solar simulator spectral irradiance.

The text of this standard is based on the following documents:

FDIS	Report on voting
82/1756/FDIS	82/1775/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 web site.

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- withdrawn,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.

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PHOTOVOLTAIC DEVICES –

Part 9: Classification of solar simulator characteristics

1 Scope

IEC standards for photovoltaic devices require the use of specific classes of solar simulators deemed appropriate for specific tests. Solar simulators can be either used for performance measurements of PV devices or endurance irradiation tests. This part of IEC 60904 provides the definitions of and means for determining simulator classifications at the required irradiance levels used for electrical stabilization and characterisation of PV devices.

This document is applicable for solar simulators used in PV test and calibration laboratories and in manufacturing lines of solar cells and PV modules. The A+ category is primarily intended for calibration laboratories and is not considered necessary for power measurements in PV manufacturing and in qualification testing. Class A+ has been introduced because it allows for reduction in the uncertainty of secondary reference device calibration, which is usually performed in a calibration laboratory. Measurement uncertainty in PV production lines will directly benefit from a lower uncertainty of calibration, because production line measurements are performed using secondary reference devices.

In the case of PV performance measurements, using a solar simulator of a particular class does not eliminate the need to quantify the influence of the simulator on the measurement by making spectral mismatch corrections and analysing the influences of spatial non-uniformity of irradiance in the test plane and temporal stability of irradiance on that measurement. Test reports for PV devices tested with the simulator report the class of simulator used for the measurement and the method used to quantify the simulator's effect on the results.

The purpose of this document is to define classifications of solar simulators for use in indoor measurements of terrestrial photovoltaic devices. Solar simulators are classified as A+, A, B or C based on criteria of spectral distribution match, irradiance non-uniformity in the test plane and temporal instability of irradiance. This document provides the required methodologies for determining the classification of solar simulators in each of the categories. A solar simulator which does not meet the minimum requirements of class C cannot be classified according to this document.

For spectral match classification a new procedure has been added. This procedure addresses the actual need for an extended wavelength range, which is arising from advances in solar cell technology (such as increased spectral responsivity below 400 nm) as well as solar simulator technology (use of component LEDs). The procedure of the second edition of this standard is still valid, but is only applied if backward compatibility of classification for solar simulators already in use and for solar simulators in production/sale is required. This document is referred to by other IEC standards, in which class requirements are laid down for the use of solar simulators. The solar simulator characteristics described in this document are not used in isolation to imply any level of measurement confidence or measurement uncertainty for a solar simulator application (for example, PV module power measurement). Measurement uncertainties in each application depend on many factors, several of which are outside the scope of this document:

- Characteristics of the solar simulator, possibly including characteristics not covered by this document;
- Methods used to calibrate and operate the solar simulator;
- Characteristics of the device(s) under test (for example, size and spectral responsivity);
- Quantities measured from the device(s) under test, including equipment and methods used for measurement;

- Possible corrections applied to measured quantities.

When applications require a certain solar simulator characteristic, it is preferable to specify a numerical value rather than a letter classification (for example, "≤ 5 % non-uniformity of irradiance" rather than "Class B non-uniformity of irradiance"). If not obvious from the application, it should also be indicated how the required simulator characteristic correlates to relevant measured quantities. Since PV module power measurement is one of the most common applications for solar simulators, brief guidance on this application is given in informative notes for each solar simulator characteristic described in this document. This document is used in combination with IEC TR 60904-14, which deals with best practice recommendations for production line measurements of single-junction PV module maximum power output and reporting at standard test conditions. For output power characterization of PV devices, IEC TR 60904-14 addresses the relevance of the letter grades (A+, A, B, C) for measurement uncertainty.

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

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

IEC TR 60904-14:– [1], *Photovoltaic devices – Part 14: Guidelines for production line measurements of single junction PV module maximum power output and reporting at standard test conditions*

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 together with the following, 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

3.1
solar simulator
equipment employing a light source with a spectral distribution similar to the natural sunlight used to evaluate characteristics of PV devices

Note 1 to entry: Simulators usually consist of three main components:

a) light source(s) and associated power supply;

b) any optics and filters required to modify the output beam to meet the classification requirements; and

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[1] Under preparation. Stage at the time of publication: 82/1748/DTR.

c) the necessary controls to operate the simulator. If the system is used for maximum power determination of PV modules, the I-V data acquisition system shall be additionally regarded as integral part. Solar simulators shall be labelled by their mode of operation during a test cycle. These are steady state, single pulse, and multi-pulse.

Note 2 to entry: Various types of solar simulators are commonly used to determine the current-voltage (I-V) characteristics of PV devices as defined in IEC 60904-1. Generally, these work as single lamp systems where the PV device is placed in the designated test area or multiple lamp systems, which are based on the superposition of light cones. Examples include:

a) Pulsed single lamp or multilamp solar simulator operated in a dark room with typically several metres distance between light source(s) and PV device. Internal reflections from walls may be suppressed by use of baffles.

b) Pulsed solar simulator operated in a casing or in tabletop configuration with typically less than 1 m distance between light source(s) and PV device. Diffuser plates and reflectors may be used to achieve the specified spatial uniformity of irradiance.

c) Steady state single lamp or multilamp solar simulator operated in a dark room with typically several metres distance between light source(s) and PV device. Internal reflections from walls may be suppressed by use of baffles.

d) LED based multilamp solar simulator operated with typically less than 1 m distance between light source(s) and PV device.

Note 3 to entry: Pulsed solar simulators can be further subdivided into long pulse systems acquiring the total I-V characteristic or a section of the I-V characteristic during one flash and systems acquiring one I-V data point per flash. Several lamp types may be used in a multilamp solar simulator. These instruments are spectrally tuneable instruments, which work with superposition of different spectral irradiances, emitted from various lamp types. If available, in addition to the rating, the reported test data should be referred to for evaluation of the applicability of the solar simulator for a specific use or testing purposes.

Note 4 to entry: Multilamp systems can be further subdivided into systems, where each lamp irradiates the total test area, and systems, where a single lamp just irradiates a part of the test area.

Besides the light source, the lamp power supply and the optics, also the I-V data acquisition, the electronic load and the operating software may be an integral part of the solar simulator. Requirements for the related measurement technique are included in other parts of the IEC 60904 series.

3.2
test plane
plane intended to contain the device under test

3.3
designated test area
region of the test plane that is assessed for solar simulator classification

Note 1 to entry: If required, typical geometries can be specified. A specification related to a circular geometry is also permitted.

3.4
data sampling time
time to take a single data set (irradiance, voltage, current). In the case of simultaneous measurement, this is given by the characteristic of the A/D converter. In the case of multiplexed systems the data sampling rate is the multiplexing rate.

Note 1 to entry: In the case of simultaneous measurement, the data sampling time is given by the characteristic of the A/D converter. In the case of multiplexed systems the data sampling time is the multiplexing rate.

The data sampling time is used for evaluation of temporal stability.

EXAMPLE In the case of non-simultaneous measurement, a multiplexing time of 1 µs would give a sampling rate of 1 Mega samples per second; the data sampling time would be 3 µs.

3.5
data acquisition time
time to take the entire or a part of the I-V curve of a PV device

Note 1 to entry: The data acquisition time depends on the number of I-V data points and a delay time that might be adjustable.

Note 2 to entry: In the case of pulsed solar simulators the data acquisition time is related to the measurements recorded during a single flash.

3.6
time for acquiring the I-V characteristic
time for acquiring the entire I-V characteristic of a PV device

Note 1 to entry: If the I-V characteristic of the PV device is measured in a single flash it is equal to the data acquisition time.

Note 2 to entry: If the I-V characteristic of the PV device is measured through sectoring in different parts with multiple flashes, it is the sum of data acquisition times for the single sectors of the IV characteristic.

3.7
spectral range
reference spectral distribution of sunlight at Air Mass 1,5 Global (AM1.5), defined in IEC 60904-3. For simulator evaluation purposes two wavelength ranges are defined:

a) Restricted wavelength range (400 nm to 1 100 nm): This definition shall establish backward compatibility to IEC 60904-9 Ed.2:2007. Spectral match evaluation is performed in the 6 wavelength bands given in Table 1.
b) Extended wavelength range (300 nm to 1 200 nm): In accordance with Table 2 the total wavelength range is divided into 6 wavelength bands, each contributing the same percentage to the integrated irradiance.

3.8
spectral match
spectral match of a solar simulator defined by the deviation from AM1.5 reference spectral irradiance as laid down in IEC 60904-3

Note 1 to entry: For six wavelength intervals of interest, the percentage of total irradiance is specified in Table 1 and Table 2. Table 1 shall be referenced if backward compatibility to the Edition 2 of this document is required.

Table 1 – Global reference solar spectral irradiance distribution given in IEC 60904-3 contribution of wavelength intervals to total irradiance in the restricted wavelength range 400 nm to 1 100 nm

	Wavelength range nm	Percentage of total irradiance in the wavelength range 400 nm to 1 100 nm %	Cumulative integrated irradiance %
1	400 to 500	18,4	18,4
2	500 to 600	19,9	38,3
3	600 to 700	18,4	56,7
4	700 to 800	14,9	71,6
5	800 to 900	12,5	84,1
6	900 to 1 100	15,9	100,0

Table 2 – Global reference solar spectral irradiance distribution given in IEC 60904-3 contribution of wavelength intervals to total irradiance in the extended wavelength range 300 nm to 1 200 nm

	Wavelength range nm	Percentage of total irradiance in the wavelength range 300 nm to 1 200 nm %	Cumulative integrated irradiance %
1	300 to 470	16,61	16,61
2	470 to 561	16,74	33,35
3	561 to 657	16,67	50,02
4	657 to 772	16,63	66,65
5	772 to 919	16,66	83,31
6	919 to 1 200	16,69	100,00

Note 2 to entry: It is generally recognized that this classification does not allow for prediction of PV module power measurement uncertainties. The methods of IEC 60904-7 and this document's Annex A should be used to understand and potentially correct for spectral mismatch errors.

3.9
spatial non-uniformity of irradiance in the test plane

$$Non-uniformity\,(\%) = \left(\frac{max.irradiance - min.irradiance}{max.irradiance + min.irradiance}\right) \cdot 100\% \quad (1)$$

where the maximum and minimum irradiance are those measured with the detector(s) over the designated test area.

Note 1 to entry: Often, a wide range of values for non-uniformity of irradiance can produce errors < 1 % in PV module power measurements, though this should be analysed on a case-by-case basis. Various publications on this topic are given in the bibliography.

3.10
temporal instability of irradiance

$$Temporal\ instability = \left(\frac{max.irradiance - min.irradiance}{max.irradiance + min.irradiance}\right) \cdot 100\% \quad (2)$$

where the maximum and minimum irradiance are those measured within the relevant time interval.

Note 1 to entry: Temporal instability is defined by two relevant time intervals:

a) Short term instability (STI)

This relates to the data sampling time of a data set (irradiance, current, voltage) during an I-V measurement. This value of temporal instability may be different between data sets on the I-V curve. In that case the short term instability is determined by the worst case.

For batch testing of cells or modules with no irradiance monitoring during I-V measurement the STI is irrelevant and LTI related to the time period between irradiance determinations shall be used for classification.

b) Long term instability (LTI)

This is related to the time period of interest. Three cases can be distinguished:

– For a three channel I-V measurement (irradiance, current, voltage) with a pulsed or steady-state solar simulator, the LTI value is the time for acquiring the I-V characteristic.

- For a two channel I-V measurement (voltage, current) with a pulsed or steady-state solar simulator, irradiance shall be measured before and after I-V measurement. The LTI value shall be calculated from these two irradiance values. The LTI value may depend on the I-V data acquisition time and the stability of the light source. The maximum averaging interval for irradiance shall correspond to the time interval between I-V data points.
- For irradiation exposure LTI shall be verified for the specifications (time period, data recording interval for irradiance) given by the supplier. If such information is not available LTI shall be related to at least 100 irradiance values, with a minimum of one data point per hour, taken at equal intervals over the exposure period.

Note 2 to entry: Irradiance corrections, such as those of IEC 60891, are often used to minimize the effects of irradiance fluctuations on PV module output power measurements. The uncertainty related to irradiance correction will depend on the difference “measured irradiance –target irradiance” and the precision of relevant I-V correction parameters of the PV device. For other applications, the use of such corrections should be considered together with requirements for solar simulator temporal instability.

3.11
solar simulator classification
a solar simulator may be one of four classes (A+, A, B, or C) for each of the three categories – spectral match, spatial non-uniformity and temporal instability. Each simulator is rated with three letters in order of spectral match, non-uniformity of irradiance in the test plane and temporal instability of irradiance.

EXAMPLE: CBA, meaning a class C spectral match, a class B spatial non-uniformity and a class A temporal instability.

Note 1 to entry: The solar simulator classification should be periodically checked in order to prove that classification is maintained. For example spectral irradiance may change with operation time of the used lamp, or uniformity of irradiance may be influenced by the reflection conditions in the test chamber.

3.12
AM1.5 spectral coverage
SPC
the SPC parameter identifies wavelength ranges, where solar simulator spectral irradiance is larger than 10 % of AM1.5 reference spectral irradiance as laid down in IEC 60904-3. For all data points fulfilling this condition the corresponding AM1.5 reference spectral irradiance is integrated. SPC is the ratio of the resulting value and the total AM1.5 solar irradiance in the range 300 nm to 1 200 nm.

$$SPC = \left(\sum_{E_{SIM}(\lambda) > 0.1 * E_{AM1.5}(\lambda)} E_{AM1.5}(\lambda) \cdot \Delta\lambda \Big/ \sum_{300\ nm}^{1200\ nm} E_{AM1.5}(\lambda) \cdot \Delta\lambda \right) \cdot 100\% \quad (3)$$

Note 1 to entry: A high value of SPC is in principle more desirable than a low value of SPC. In this document no requirements for this parameter will be defined.

Note 2 to entry: No specific guidance can be given at this time regarding its use for assessing PV module output power measurement uncertainties.

3.13
AM1.5 spectral deviation
SPD
within the wavelength ranges defined in Table 2, spectral irradiance values may be higher or lower than AM1.5 reference spectral irradiance as laid down in IEC 60904-3. These deviations are not detected by spectral match. The SPD parameter represents the summed deviation between both curves and indicates how well the solar simulator spectral irradiance matches with AM1.5 spectral irradiance:

$$SPD = \sum_{300nm}^{1200\ nm} |E_{SIM}(\lambda) - E_{AM1.5}(\lambda)| \cdot \Delta\lambda \Big/ \sum_{300\ nm}^{1200\ nm} E_{AM1.5}(\lambda) \cdot \Delta\lambda \cdot 100\% \quad (4)$$

Note 1 to entry: A low value of SPD is in principle more desirable than a high value of SPD. Values for SPD may exceed 100 %. In this document no requirements for this parameter are defined.

Note 2 to entry: The parameter SPD is also used for characterizing light sources in non-photovoltaic applications (EN 13032-1). No specific guidance can be given at this time regarding its use for assessing PV module power measurement uncertainties.

4 Classification of solar simulator characteristics

Table 3 gives the performance requirements for the three characteristics spectral match, non-uniformity of irradiance and temporal instability of irradiance.

For the spectral match, all six intervals shown in Table 1 or Table 2 shall agree with the ratios in Table 3 to obtain the respective classes.

- Spectral irradiance of solar simulators shall be evaluated in the extended wavelength range according to Table 2.
- Solar simulators in use and solar simulators in production/sale that have been classified under Edition 2 of this document make an exception. Spectral irradiance of these can be re-evaluated according to the same method (that of Edition 2) in the restricted wavelength range. For that purpose Table 1 shall be referenced. This exception shall ensure the backward compatibility, if required.
- If a significant change of PV technology occurred in the production of PV devices, the customer is encouraged to perform spectral classification in the extended wavelength range and use Table 2 to re-evaluate the simulator. In addition the sensitivity analysis for spectral mismatch uncertainty as of Annex A shall be applied.
- The method used for the spectral classification renewal (restricted or extended wavelength range) should be clearly stated in the report.

Refer to Clause 5 for procedures to measure and calculate the three characteristics of the simulator (spectral match, non-uniformity of irradiance and temporal instability of irradiance). In addition the parameters SPC and SPD shall be calculated. These results for SPC and SPD are informative.

If stated by the manufacturer a number of flashes or on-time to stabilize irradiance should be done prior to the classification.

These requirements apply to both steady state and pulsed solar simulators.

Table 3 – Definition of solar simulator classifications

Classifications	Spectral match to all intervals specified in Table 1 or Table 2	Spatial non-uniformity of irradiance %	Temporal instability	
			Short term instability of irradiance STI %	Long term instability of irradiance LTI %
A+	0,875 to 1,125	1	0,25	1
A	0,75 to 1,25	2	0,5	2
B	0,6 to 1,4	5	2	5
C	0,4 to 2,0	10	10	10

Class A+ is only defined for the three solar simulator characteristics, if spectral match evaluation is performed in the extended wavelength range according to Table 2.

NOTE Spatial non-uniformity of irradiance corresponding to Class A+ is consistent with the requirements specified in IEC 60904-2 for calibration of reference devices using simulated sunlight.

If spectral match evaluation is performed in the restricted wavelength range according to Table 1, only the classifications A, B and C are permitted for each solar simulator characteristic (backward compatibility to previous Edition of this document).

Practical examples for different applications of solar simulators are given in IEC TR 60904-14.

5 Measurement procedures

5.1 Introductory remarks

It is the intent of this document to provide guidance on the required solar simulator performance data to be taken, and the required locations in the designated test area for these data to be taken. It is not the intent of this document to define the possible methods to determine the simulator spectrum or the irradiance at any location on the test plane. It is the responsibility of the simulator manufacturer or test laboratory to provide information upon request for test methods used in the determination of the performance in each classification. The classification of a solar simulator does not provide full information about sources of measurement uncertainty that are related to PV performance measurements obtained with a classified solar simulator. Such uncertainties are dependent on the actual measurement devices and procedures used and need to be evaluated.

In general, the classification of solar simulators will depend on a number of factors. Also most simulators can be operated at different working points (for example different irradiances). In this case, the classification is only valid for the conditions similar to those during classification assessment. If the intended use of the solar simulator includes a change of irradiance levels, classification shall be performed and reported at these irradiance levels ± 50 W/m^2.

Classification of a solar simulator is not constant but subject to various factors:

– Ageing of lamp with operation time.

– Exchange of lamp(s.)

– Lamp power setting.

– Use of any inserts in the beam of light such as optical filters or (light reducing) masks or meshes.

– Ageing or soiling of any inserts.

– Reflections from the surroundings such as properties of dark room walls.

– Pulse duration, if applicable.

Accordingly, classification only refers to the actual operating conditions. Ideally, classification as stated in the product specification or test report shall cover the range of operating conditions during practical use. Classification should be reviewed periodically.

5.2 Spectral match

5.2.1 General

Spectral match may change during the pulse of a pulsed solar simulator and is subject to spatial non-uniformity. Integration time for spectral irradiance measurement should be adjusted to the data acquisition time and spectral match should be calculated for that time period.

5.2.2 Apparatus

The spectroradiometer shall be appropriate for the measurement task. Ensure that the sensitivity of the sensor is suitable for the wavelength range of interest. The time constant