SRI LANKA STANDARD 1545 PART 2 : 2017

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SPECIFICATION FOR
PHOTOVOLTAIC (PV) MODULE PERFORMANCE TESTING AND ENERGY RATING

PART 2: SPECTRAL RESPONSIVITY, INCIDENCE ANGLE AND MODULE OPERATING TEMPERATURE MEASUREMENTS

SRI LANKA STANDARDS INSTITUTION

Sri Lanka Standard Specification for

PHOTOVOLTAIC (PV) MODULE PERFORMANCE TESTING AND ENERGY RATING
PART 2: SPECTRAL RESPONSIVITY, INCIDENCE ANGLE AND MODULE OPERATING TEMPERATURE MEASUREMENTS

SLS 1545 Part 2: 2017
IEC 61853-2: 2016

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Sri Lanka Standards are subject to periodical revision in order to accommodate the progress made by industry. Suggestions for improvement will be recorded and brought to the notice of the Committees to which the revisions are entrusted.
This standard does not purport to include all the necessary provisions of a contract.

Sri Lanka Standard Specification for
PHOTOVOLTAIC (PV) MODULE PERFORMANCE TESTING AND ENERGY RATING
PART 2: SPECTRAL RESPONSIVITY, INCIDENCE ANGLE AND MODULE OPERATING TEMPERATURE MEASUREMENTS

NATIONAL FOREWORD

This standard was approved by the Sectoral Committee on Electronic Engineering and was authorized for adoption and publication as a Sri Lanka Standard by the Council of Sri Lanka Standards Institution on 2017-02-24.

SLS 1545 Sri Lanka Standard Specification for Photovoltaic (PV) module performance testing and energy rating, part 2: spectral responsivity, incidence angle and module operating temperature measurements**.** This part of standard is identical with IEC 61853 Photovoltaic (PV) module performance testing and energy rating, Part 2: 2016 Edition 1.0 spectral responsivity, incidence angle and module operating temperature measurements**,** published by the International Electrotechnical Commission (IEC).

All values given in this standard is in SI units.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or an analysis shall be rounded off in accordance with SLS 102, in case if the method of rounding off is not specified in the text of this standard. The number of figures to be retained in the rounded off value, shall be the same as that of the specified value in this standard.

Terminology and conventions

The text of the International Standard has been accepted as suitable for publication, without any deviation as a Sri Lanka Standard. However, certain terminology and conventions are not identical with those used in Sri Lanka Standards; attention is therefore drawn to the following:

a) Wherever the words "International Standard" appear referring to this standard they should be interpreted as "Sri Lanka Standard".

b) Wherever the page numbers are quoted they are the page numbers of IEC standard.

c) The comma has been used as a decimal marker. In Sri Lanka Standards it is the current practices to use a full point on the base line as a decimal marker.

d) Attention is drawn to the possibility that some of the elements of the Sri Lanka Standard may be the subject of patent rights. SLSI shall not be held responsible for identifying any or all such patent rights.

CROSS REFERENCES

International Standards	Corresponding Sri Lanka Standards
IEC 61215 (all parts), Terrestrial photovoltaic (PV) modules – Design qualification and type approval	SLS 1544 (all parts), Terrestrial photovoltaic (PV) modules – Design qualification and type approval
IEC 61215-2, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures	SLS 1544 Part 2, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures
IEC 61853-1:2011, Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating	SLS 1545 Part 1, Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating

Any corresponding Sri Lanka Standard, for the international standards listed under reference, is not available.

SLS 1545-2:2017

IEC 61853-2

Edition 1.0 2016-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Photovoltaic (PV) module performance testing and energy rating –
Part 2: Spectral responsivity, incidence angle and module operating temperature measurements

Essais de performance et caractéristiques assignées d'énergie des modules photovoltaïques (PV) –
Partie 2: Mesurages de réponse spectrale, d'angle d'incidence et de température de fonctionnement des modules

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PHOTOVOLTAIC (PV) MODULE PERFORMANCE TESTING AND ENERGY RATING –

Part 2: Spectral responsivity, incidence angle and module operating temperature measurements

FOREWORD

International Standard IEC 61853-2 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

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

FDIS	Report on voting
82/1133/FDIS	82/1156/RVD

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

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

A list of all parts in the IEC 61853 series, published under the general title *Photovoltaic (PV) module performance testing and energy rating*, can be found on the IEC website.

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

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

INTRODUCTION

Photovoltaic (PV) modules are typically rated at standard test conditions (STC) of 25 °C cell temperature, 1 000 $W \cdot m^{-2}$ irradiance, and air mass (AM) 1.5 global (G) spectrum. However, the PV modules in the field operate over a range of temperatures, irradiance, and spectra. To accurately predict the energy production of the modules under various field conditions, it is necessary to characterize the modules at a wide range of temperatures, irradiances, angles of incidence, and spectra.

Recognizing this issue, IEC Technical Committee 82 Working Group 2 (TC 82/WG 2) has developed an appropriate power and energy rating standard (IEC 61853). The first part of this four-part standard requires the generation of a 23-element maximum power (P_{max}) matrix at four different temperatures and seven different irradiance levels. The P_{max} matrix can be generated using an indoor solar simulator method or outdoor natural sunlight method. The outdoor test method introduces little/no spectral mismatch error and is much less expensive than the indoor test method because it avoids the use of very expensive solar simulators. However, obtaining an accurate and repeatable P_{max} matrix using the outdoor method over time (several months or years) would be extremely challenging.

This standard consists of four parts:

- IEC 61853-1: *Irradiance and temperature performance measurements and power rating*, which describes requirements for evaluating PV module performance in terms of power (watts) rating over a range of irradiances and temperatures;
- IEC 61853-2: *Spectral responsivity, incidence angle, and module operating temperature measurements*, which describes test procedures for measuring the effect of varying angle of incidence and sunlight spectra as well as the estimation of module temperature from irradiance, ambient temperature, and wind speed;
- IEC 61853-3[1]: *Energy rating of PV modules*, which describes the calculations for PV module energy (watt-hours) ratings; and
- IEC 61853-4[2]: *Standard reference climatic profiles*, which describes the standard time periods and weather conditions that can be used for the energy rating calculations.

Included in the IEC 61853 series of standards are: test methods designed to map module performance over a wide range of temperature and irradiance conditions (IEC 61853-1); test methods to determine spectral responsivity, incidence angle effects and the module operating temperature all as functions of ambient conditions (IEC 61853-2); methods for evaluating instantaneous and integrated power and energy results including a method for stating these results in the form of a numerical rating (IEC 61853-3); and definition of reference irradiance and climatic profiles (IEC 61853-4).

IEC 61853-1 describes requirements for evaluating PV module performance in terms of power (watts) rating over a range of irradiances and temperatures. IEC 61853-2 describes procedures for measuring the performance effect of angle of incidence, the estimation of module temperature from irradiance, ambient temperature and wind speed, and impact of spectral responsivity on module performance. IEC 61853-3 describes the calculations of PV module energy (watt-hours) ratings. IEC 61853-4 describes the standard time periods and weather conditions that can be utilized for calculating energy ratings.

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1 Under preparation: Stage at the time of publication: IEC/ACDV 61853-3:2016.

2 Under preparation: Stage at the time of publication: IEC/ACDV 61853-4:2016.

IEC published the first part of the standard in January 2011. This standard specifies the performance measurements of PV modules at 23 different sets of temperature and irradiance conditions, using either a solar simulator (indoor) or natural sunlight (outdoor). There are many possible indoor and outdoor techniques, and this standard allows several of them. Validation of these techniques for repeatability over time within the same laboratory and for reproducibility among multiple laboratories is extremely important for the successful implementation of this standard.

PHOTOVOLTAIC (PV) MODULE PERFORMANCE TESTING AND ENERGY RATING –

Part 2: Spectral responsivity, incidence angle and module operating temperature measurements

1 Scope

The IEC 61853 series establishes IEC requirements for evaluating PV module performance based on power (watts), energy (watt-hours) and performance ratio (PR). It is written to be applicable to all PV technologies, but may not work well for any technology where the module performance changes with time (e.g. modules change their behaviour with light or thermal exposure), or which experience significant non-linearities in any of their characteristics used for the modelling.

The purpose of this part of IEC 61853 is to define measurement procedures for measuring the effects of angle of incidence of the irradiance on the output power of the device, to determine the operating temperature of a module for a given set of ambient and mounting conditions and measure spectral responsivity of the module. A second purpose is to provide a characteristic set of parameters which will be useful for detailed energy predictions. The described measurements are required as inputs into the module energy rating procedure described in IEC 61853-3.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60410[3], *Sampling plans and procedures for inspection by attributes*

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 60904-5, *Photovoltaic devices – Part 5: Determination of equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*

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

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

IEC 60904-10, *Photovoltaic devices – Part 10: Methods of linearity measurement*

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3 Withdrawn.

IEC 61215 (all parts), *Terrestrial photovoltaic (PV) modules – Design qualification and type approval*

IEC 61215-2, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures*

IEC 61646, *Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval*

IEC 61853-1:2011, *Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating*

ISO 9059, *Solar energy – Calibration of field pyrheliometers by comparison to a reference pyrheliometer*

3 Sampling

For performance qualification testing, three modules shall be selected at random from a production batch or batches in accordance with the procedure given in IEC 60410. The modules shall be pre-conditioned in accordance with Clause 4 of this standard to assure the stability of the power values. One module (or equivalent reference sample) shall be used for each of the three tests, angle of incidence, spectral responsivity and thermal performance. A single module may be supplied if the test is to be carried out serially or three modules need to be supplied if it is to be carried out in parallel.

The modules shall have been manufactured from specified materials and components in accordance with the relevant drawings and process sheets and shall have been subjected to the manufacture's normal inspection, quality control and production acceptance procedures. The modules shall be complete in every detail and shall be accompanied by the manufacturer's handling and final assembly instructions regarding the recommended installation of any diodes, frames, brackets, etc.

When the DUTs (device under test) are prototypes of a new design and not from production, this fact shall be noted in the test report (see Clause 5).

4 Testing

One of the modules, or representative samples, shall be subjected to each of the testing procedures defined in Clauses 6 to 8, i.e. the procedure for spectral responsivity (see Clause 6), angle of incidence (see Clause 7) and module operating temperature measurements (see Clause 8). In carrying out the tests, the manufacturer's handling, cleaning, mounting and connection instructions shall be observed. This can be the same module undergoing all tests sequentially or three distinct modules undergoing the characterisation tests in parallel. It shall be noted in the test report if a single or different modules have been used.

If the module under test is going to be used with a frame that covers the edges of the superstrate, then each of the tests shall be performed with a similar frame in place.

Preconditioning – Before beginning the measurements, the device under test shall be stabilized, as specified in IEC 61215 or IEC 61646.

Figure 1 shows an overview of the testing procedure to be conducted.

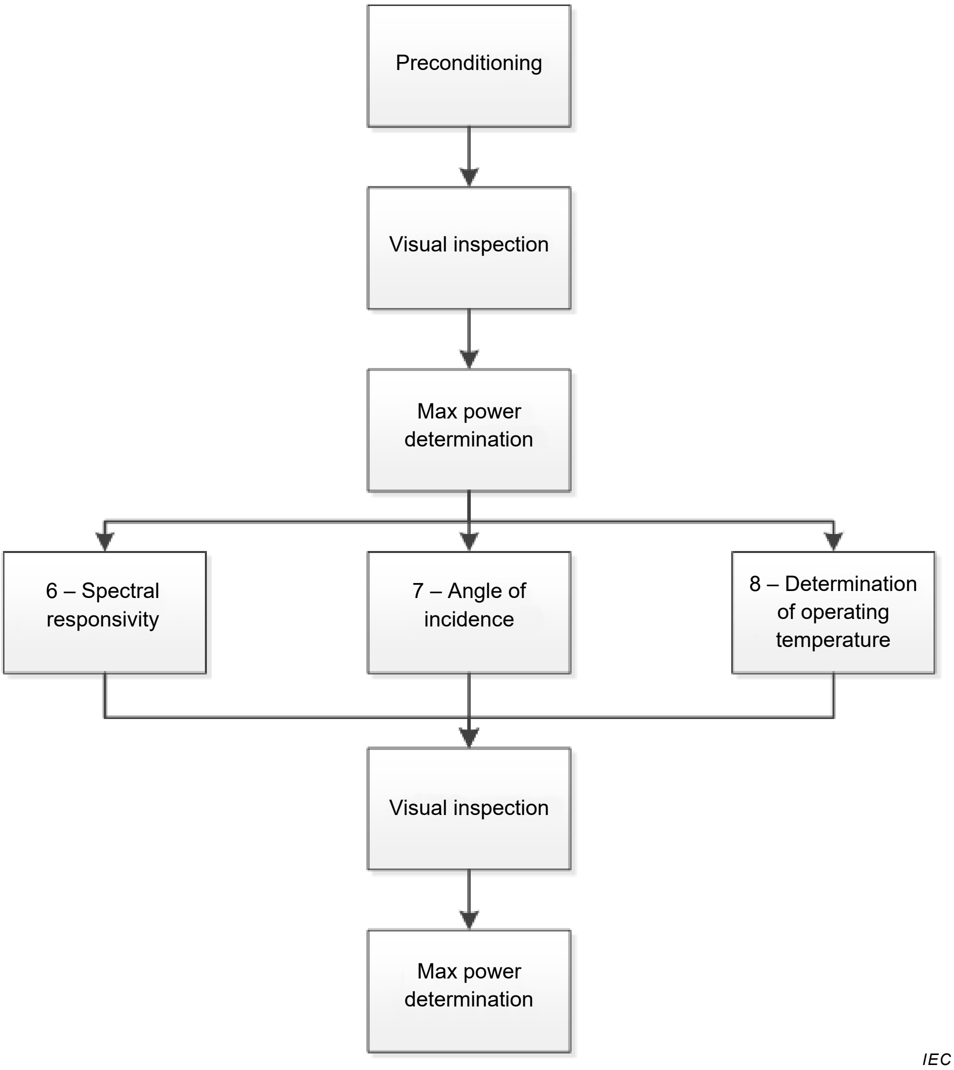

Figure 1 – Overview of the testing cycle to be carried out in IEC 61853-2

5 Report

Following completion of the procedure, a report of the performance tests, with measured module characteristics shall be prepared. Each certificate or test report shall include at least the following information:

a) a title;

b) name and address of the test laboratory and location where the calibration or tests were carried out;

c) unique identification of the certification or report and of each page;

d) name and address of client, where appropriate;

e) description and identification of the item calibrated or tested;

f) characterization and condition of the calibration or test item;

g) date of receipt of test item and date(s) of calibration or test, where appropriate;

h) identification of calibration or test method used;

i) reference to sampling procedure, where relevant;

j) any deviations from, additions to or exclusions from the calibration or test method, and any other information relevant to a specific calibration or test, such as environmental conditions, including the tilt angle of the module used during the temperature test (see 8.4.1) and limits to the field of view;

k) measurements, examinations and derived results of module incidence angle effects, its operating temperature and its spectral responsivity. The report should indicate the method used to deal with the diffuse light component for the measurement of angle of incidence (see 7.3.4);

l) for non-symmetric optical modules, the tilt and azimuth directions have to be specified in a drawing;

m) a statement of the estimated uncertainty of the calibration and test result (where relevant);

n) a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of the certificate or report, and the date of issue;

o) where relevant, a statement to the effect that the results relate only to the items calibrated or tested;

p) a statement that the certificate or report shall not be reproduced except in full, without the written approval of the laboratory.

6 Procedure for spectral responsivity measurement

The spectral responsivity of a PV module has an impact on the amount of current produced at any given spectral irradiance. Normally it is not necessary to measure the spectral responsivity at all possible values of irradiance and temperature that a module encounters during outdoor operation. A single measurement should be sufficiently accurate for all expected operating conditions. The need for this can be verified by checking the linearity of short circuit conditions measured in IEC 61853-1. Should a non-linearity of I_{sc} with respect to irradiance or temperature larger than 3 % be observed, further investigation might be warranted to identify if the SR changes as a function of irradiance and temperature (If the spectral responsivity of a particular module type is a function of irradiance or temperature, this result fact should appear in the test report).

To measure the spectral responsivity, follow the procedure as laid out in IEC 60904-8 using the short circuit condition, 25 °C device temperature and an appropriate bias light. This procedure should be applied to the full-sized module if possible, i.e. the module should be characterized in its entirety. If this is not possible, a small sample equivalent in construction and materials may be used or a single cell in the module should be characterized according to the measurements described in IEC 60904-8.

The spectral responsivity of a solar cell changes upon encapsulation. Therefore, an encapsulated solar cell shall be used if a full-sized module cannot be tested.

The module power shall be measured after measurement of the spectral responsivity. Any changes shall be noted in the test report.

7 Procedure for the measurement of incidence angle effects

7.1 Purpose

The purpose of the incident angle test is to determine the effect of solar incidence angles on module performance. The incidence angle dictates the fraction of the direct and diffuse irradiance available for conversion into electrical energy inside the module, i.e. the transmitted and reflected fractions of the available light. Both the external (the front surface) reflection and internal reflections are functions of the solar incidence angle and of the module design. Hence, the irradiance absorbed by PV devices at a particular incidence angle may differ between module designs. Also, the orientation of the module installation has a strong influence on the incidence angle effects.

For modules with a flat uncoated front glass plate, the relative light transmission into the module is primarily influenced by the first glass-air interface. The test can be omitted if the interface is flat and no antireflective coating is applied. The data of a flat glass-air interface can be used. However, normally glasses used for solar modules are somewhat structured and thus it is recommendable to carry out a verification measurement in either case.

Although the relative light transmission into the module is primarily influenced by the glass air interface, the details of other optical interfaces and other measures to enhance optical confinement might be relevant as well. If there is reason to believe that the other optical interfaces have been significantly changed, the test should be conducted.

This document presents two unequal alternatives (indoor and outdoor approach) which might not necessarily yield identical results but results should be equivalent within their uncertainties. It should be noted in the test report, which method has been used.

7.2 Indoor test method

7.2.1 General

The test method for the incident angle test is based on gathering actual measured I_{sc} data for the test modules over a wide range of incidence angles. If no light source with light uniformity in the volume spanned by a full module upon rotation is available (see 7.2.2c), a smaller, optically equivalent test module with one active cell, surrounded by non-active cells, may be tested. In the following, the area of the active cell is referred to as measurement area and all specification shall be met for this area only to allow realistic measurements. The area of influence is the active cell plus one half cell dimension in all directions.

7.2.2 Apparatus

The following apparatus is required to control and measure the test conditions:

a) A PV reference device in conformance with IEC 60904-2 that is linear in output over the range of irradiance variations of the solar simulator according to IEC 60904-10, mounted fixed in the test plane of the simulator to monitor the total irradiance of the solar simulator.

b) Means of measuring the temperature of the ambient, the test module and the reference device to an accuracy of ±1 °C with a repeatability of ±0,5 °C.

c) A solar simulator of class B with respect to the spatial uniformity requirements within the measurement area and class C over the area of influence and with respect to temporal stability according to IEC 60904-9. The solar simulator should have minimal irradiance outside a 30° field of view. It is recommended that the solar simulator should have 95 % of its irradiance within 10° field of view. The spatial uniformity requirement (class B) shall be fulfilled in the volume that is covered by the active element(s) within the module during rotation. The area of influence should maintain class C. The solid angle of the light of the simulator should not vary by more than 1° over the active area of the test device. The spatial uniformity of the active area and the area of influence shall be stated in the report.

   NOTE The depth of the volume is determined by the highest inclinations and a detailed assessment of the worst case needs to be carried out in advance of the measurements.

d) Equipment to measure the short circuit current of the test module to an accuracy of ±0,2 % of the value at 1 000 $W \cdot m^{-2}$ (see IEC 60904-1).

e) Equipment for measuring the reference device output to an accuracy of ±0,2 % of the value at 1 000 $W \cdot m^{-2}$.

f) An adjustable rack capable of accurately positioning the module at the specified angles of incidences to an accuracy of ±1°. Care shall be taken to ensure that rotation of the test apparatus does not change the irradiance on the reference device. The device should be rotated around the rotational axis of the cell centre under investigation. The rotational axis shall not change during the entire angular range of measurements.

g) Module temperature sensors, attached by solder or thermally conducive adhesive to the backs of two solar cells near the middle of each test module, or to the back of the active cell if an optically equivalent mini-module is used. Alternatively, use IEC 60904-5 and its associated equipment for determining cell temperature. The total accuracy of the module temperature determination shall be ±1 °C.

h) A data acquisition system capable of recording the following parameters for each angle setting:
   - reference device output,
   - short circuit current of the module,
   - module temperature,
   - reference device temperature.

The measurement of module current and reference device output shall be simultaneous.

7.2.3 Set-up procedure

The set-up procedure is as follows.

a) Make sure that the front surface of the module is clean.

   It is acceptable to mechanically isolate and contact a single crystalline cell, i.e. cut through the back sheet to access the contacts of a single cell directly. In the case of thin film modules one would need to manufacture a specific test device with a single cell, or an area of interest, being contacted separately and isolated for these measurements.

b) Mount the module in the test plane of the simulator so that it is normal to the centre line of the beam within ±1°. Connect to the necessary instrumentation.

c) If the test system is equipped with temperature controls, set the controls at the desired level. If temperature controls are not used, allow the module to stabilize within ±1 °C of the room air temperature.

d) Set the irradiance at the test plane of the simulator to 1 000 $W \cdot m^{-2}$ at perpendicular incidence using the reference device. Maintain this irradiance throughout the measurements. If this is not possible, a value in the range of 700 $W \cdot m^{-2}$ to 1 000 $W \cdot m^{-2}$ (see IEC 60891) is sufficient.

Care shall be taken to prevent reflection from within the room. There shall be no protrusions to prevent full irradiance of the test module during the measurement. Reflections off the floor, walls or ceiling or objects shall be avoided.

Some black paints are highly reflective in the infrared. It is recommended to test the reflective properties of the paint used to assess the uncertainties of the procedure.

7.2.4 Measurement procedure

Measurements should be taken along two orthogonal angular directions with respect to the module normal. In cases of known symmetrical reflection properties, measurements in one axis are sufficient and the second axis may be omitted. Symmetrical behaviour is expected if samples with similar cells and the same front glass have been shown to be symmetrical.

The following procedure assumes symmetry in the rotational axis.

NOTE There is no knowledge of a device which does not meet this requirement.

a) At 0° rotation angle position the test cell in the test area so that the center of the cell lies in the optical axis and the axis of rotation in the middle of the cell. Rotational symmetry of the test arrangement shall be verified at –80° and 80° rotation angle. The ratios (I_{SC}, 80° / I_{SC}, 0°) / cos 80° for both directions shall not differ by more than 2 %.

b) Vary the angle between the module normal and the optical axis of the light source between –60° and + 60° in steps of a maximum of 10°. Outside that range vary the angle in steps of maximum 5°.

c) If using a steady state solar simulator, keep the module temperature close to a chosen temperature by shading the module between taking data. Alternatively, allow for the module to reach thermal equilibrium. Care shall be taken as less light irradiates the module at increasing incidence angles. Temperature differences between measurements shall be recorded and corrected for.

d) For each setting, take at least three readings of the short circuit current and module temperature. If necessary, correct for irradiance fluctuations with the help of the reference device. Correct to a module temperature of 25 °C using data from Table 2 of IEC 61853-1:2011 and average to obtain $I_{sc}(\theta)$.

e) The relative light transmission into the module is given by:

$$\tau(\theta) = I_{sc}(\theta)/(\cos(\theta)\, I_{sc}(0)) \quad (1)$$

Where θ corresponds to the angle of incidence with respect to the module normal.

Care has to be taken regarding low light level dependence: At high incidence angles, the light intensity in the module plane will be strongly reduced by the cosine law. If the short circuit current of the module has been shown to vary nonlinearly with respect to irradiance in the measurements of Table 2 of IEC 61853-1:2011, a nonlinearity correction has to be performed in addition to equation (1) using polynomial fit of the I_{sc} data generated in IEC 61853-1.

f) If the results are not symmetrical determine if the results represent an off-set in angle or if the module is truly not symmetrical (not the same on both sides of normal incidence). If it is the latter, the light transmission should be stated for both tilt directions.

The module power shall be measured after measurement of the angle of incidence responsivity. Any changes shall be noted in the test report.

7.3 Outdoor test method

7.3.1 General

The outdoor test method for the incident angle test is based on gathering measured I_{sc} data for the test modules over a wide range of incidence angles, along with associated global irradiance in the plane of the module and direct normal irradiance so that contributions to I_{sc} from both the beam and diffuse components can be distinguished.

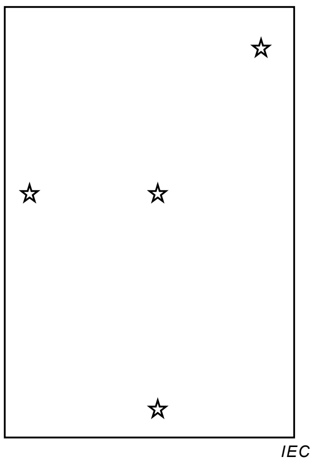

Figure 2 – Positions for measuring the temperature of the test module behind the cells

7.3.2 Apparatus

The following apparatus is required to control and measure the test conditions:

a) A calibrated pyranometer mounted in the test plane of the test module(s).

b) Optionally, a PV reference device in conformance with IEC 60904-2 linear in output over the range of irradiance variations and calibrated as a function of angle incidence mounted in the test plane of the test module. This is recommended if any site specific measurement artifacts are expected.

c) A PV reference device in conformance with IEC 60904-2 that is linear in output over the range of irradiance variations, mounted on a separate solar tracker to measure the global normal irradiance.

d) A normal incidence pyrheliometer, calibrated according to ISO 9059, to measure the direct normal component of irradiance mounted on the separate solar tracker.

e) Means of measuring the temperature of the ambient, the test module and the reference device to an accuracy of ±1 °C with a repeatability of ±0,5 °C. The module temperature should be measured in at least 4 places as shown in Figure 2.

f) Equipment to measure the short circuit current of the test module to an accuracy of ±0,2 % of the value at 1 000 W·m^{-2} (see IEC 60904-1). The test modules shall not be continuously short circuited, to avoid reverse bias conditions and individual hot cells. Rather the module should be in an open circuit or maximum power condition between short duration I_{sc} measurements.

g) Equipment for measuring the reference device output to an accuracy of ±0,2 % of the value at 1 000 W/m^2.

h) A two-axis tracker with an open rack mount and provision for introducing module angle-of-incidence values in the range from – 90° to + 90°, with at least 80° achievable.

NOTE 1 A one axis tracker may also be sufficient, but the method will have to be adapted to correct for AOI variation due to non-perpendicular sweep directions.

i) Means to determine the solar angle of incidence with an accuracy of at least ±0,5°. Mounting a module onto a tracker may not satisfy this requirement even if the tracker is capable of much better tracking accuracy. A verification of the tilt angle with an accuracy better than ±1° is required. Options include using calculated sun position angles in combination with solar tracker position angles, or digital inclinometer readings when tilt angles are varied in only the elevation axis, or a digital protractor equipped with a sun alignment feature.

NOTE 2 Determination of the solar angle of incidence (θ) with accuracy of at least ±0,5° is required; otherwise at large θ values the uncertainty associated with the cos(θ) factor becomes significant.

j) A data acquisition system to record the following parameters:
   - reference device(s) outputs,
   - short circuit current of the device(s) under test,
   - module temperatures,
   - reference device temperatures (if applicable).

The measurement of module current and reference device output shall be simultaneous (no more than 1 ms apart). Longer separation (up to 1 s) is permissible but the stability of the irradiance shall be verified by taking a measurement of the irradiance before and after module measurement.

7.3.3 Set-up procedure

Select a test period of less than 1 hour duration with optimum weather conditions; clear sky near solar noon with minimal solar spectral (air mass) variation, minimal variation in the direct to global normal G_{dni}/G_{gni} ratio, and mild wind speed < 4 m·s^{-1}.

a) Ensure that the front surface of the DUT is clean.

b) Mount the DUT in the test rack of the angle-of-incidence test system. Attach temperature sensors and connect to the necessary instrumentation.

c) If the DUT is equipped with temperature controls, set the controls at the desired level. If temperature controls are not used, position the module normal to the sun and allow the DUT's temperature to stabilize for at least 15 min, and verify that the maximum range between individual sensor temperatures is less than 5 °C.

d) Verify that the reference device and the pyrheliometer mounted on the separate tracker are perpendicularly pointing to the sun.

e) The DUT accepts light from a very wide acceptance angle, essentially ±90°, so unwanted reflections and shading from objects and structures within the view angle of the DUT shall be avoided. The ground surrounding the DUT should not have an abnormally high reflectance (albedo) and should be nominally flat in all directions surrounding the test structure.

7.3.4 Measurement procedure

The test shall be conducted during clear sky conditions when the ratio of direct normal irradiance, G_{dni}, divided by global normal irradiance, G_{gni}, is greater than 85 %. This corresponds to a condition at normal incidence to the module when the diffuse component of sunlight is less than 15 % of the total. The solar irradiance components required are defined below:

G_{gni} is the global (total) normal irradiance measured using a pyranometer that is continuously tracking the sun on separate solar tracker.

G_{dni} is the direct normal irradiance measured using a pyrheliometer that is continuously tracking the sun on separate solar tracker.

G_{tpoa} is the global (total) irradiance in the plane of the module measured by a pyranometer mounted in the module test plane and in close proximity.

$G_{diff} = G_{poa} - G_{dni} \cos(\theta)$ is the calculated diffuse component of irradiance in the plane of the test module.

θ corresponds to the angle of incidence between the module normal and the direct beam solar irradiance.

a) Use the test system to introduce a series of angle-of-incidence with respect to the direct normal solar irradiance. Vary the angle between the module normal and the sun beam by including as broad a range as possible between –90° and +90° with a maximum step size of 10° in the range –60° and +60°, and 5° outside this range. Initiate and complete the test sequence at normal incidence, θ = 0°. If position sequence permits, also include a normal incidence setting during the series of module positions.

   For test modules with optical symmetry of the front surface, e.g. planar glass surface, the direction of the angle of incidence relative to the module coordinate system is not critical, and measurements at angular positions in one direction relative to normal incidence are adequate.

   NOTE 1 It is preferable that test module orientations are used that result in view angles from the module perspective seeing primarily the sky, rather than downward orientations where the module and associated pyranometer are viewing primarily the ground.

   NOTE2 For test modules with a patterned or textured front surface, it is necessary to control the direction of the angle of incidence to provide measurements in two orthogonal directions relative to the module coordinate system.

b) For each angle-of-incidence setting, record at least three readings of the test module's short circuit current, and all module temperature sensors, and all solar irradiance sensors.

   Care should be taken for thin film modules, where operation at I_{sc} may cause damage. In case of damage, the short circuit stability shall be verified. If the short circuit current varies by more than 1 % at STC, the measurements are not valid. It may be that a repeat of measurements will result in stable measurements and thus a repeat measurement could be done and the I_{sc} stability should be verified for each measurement.

c) Process the measured data at each angle of incidence, θ, in the following sequence:

   i) Delete all measured values when the G_{dni}/G_{gni} ratio is less than 85 %, as a sky clearness criteria.

   ii) Calculate the average module temperature, T_m, at each θ by averaging values from all temperature sensors. Verify that the maximum variation between all individual temperature sensors is less than 5 °C.

   iii) Translate measured short circuit current values, I_{scm}, to a module temperature of 25 °C using a temperature coefficient, α_{Isc} with units of 1/°C.

$$I_{sc}(\theta) = I_{scm}(\theta) \,/\, (1+ \alpha_{Isc}\,(T_m(\theta) - 25)) \tag{2}$$

   iv) Calculate a reference short circuit current, I_{sco}, by averaging I_{sc} values at normal incidence with θ = 0°. Calculate a reference global irradiance in the plane of the module, G_{poao}, by averaging G_{poa} values at normal incidence with θ = 0°.

   v) Calculate the diffuse component of irradiance in the plane of the module, G_{diff}, at each θ by using the associated G_{dni} and G_{poa} values.

$$G_{diff}(\theta) = G_{poa}(\theta) - G_{dni}(\theta)\cos(\theta) \tag{3}$$

d) The angle-of-incidence relationship defining the relative angular light transmission into the module is then given by:

$$\tau(\theta) = (I_{sc}(\theta)\, G_{poao} - I_{sco}\, G_{diff}(\theta)) \,/\, (I_{sco}\, G_{dni}(\theta)\cos(\theta)) \tag{4}$$

NOTE 3 This method assumes that the test module responsivity (current generation) is essentially the same for the solar spectral distributions of both the direct and the diffuse components of irradiance. It also assumes for the clear sky test conditions *specified* that the test module responds to all of the measured diffuse irradiance.

e) If the test module is not optically symmetrical, the light transmission should be measured and stated for both tilt directions defined relative to module coordinates.

7.4 Interpolation of angular transmission $\tau(\theta)$

The relative light transmission into the module $\tau(\theta)$ has been measured at a number of angles, and for convenience can be reported as a single parameter in analytical function.

For the purposes of interpolation, $\tau(\theta)$ can be approximated as an analytical function. In the case of flat front covers, the following may be used:

$$\tau(\theta) = \frac{1 - \exp\dfrac{-\cos(\theta)}{a_r}}{1 - \exp\dfrac{-1}{a_r}} \tag{5}$$

The incidence angle θ is the angle between the normal of the module surface and the direction of the incoming light. The parameter a_r shall be determined from the measurements by an appropriate fitting procedure. The procedure shall provide three significant digits of a_r as well as an estimate of the uncertainty.

8 Methodology for determining coefficients for calculating module operating temperature

8.1 General

The purpose of this procedure is to determine the impact of ambient temperature, wind speed and light absorption on energy production. The temperature of a PV module is a function of the ambient temperature, irradiance, wind speed and its mounting system. Clause 8 provides the methodology to determine the relationship between ambient temperature, wind speed and irradiance for a particular mounting configuration.

8.2 Testing and data processing

The method is based on gathering actual measured module temperature data over a range of environmental conditions. The data obtained is averaged and analysed in a way that allows accurate and repeatable interpolation of the module temperature as a function of ambient temperature, irradiance and wind speed.

The temperature of the module (T_{m}) is primarily a function of the ambient temperature (T_{amb}), the wind speed (v) and the total solar irradiance (G) incident on the active surface of the module. The temperature difference ($T_{\mathrm{m}} - T_{\mathrm{amb}}$) is largely independent of the ambient temperature and is essentially linearly proportional to the irradiance at levels above 400 W·m^{-2}.

The module temperature is modelled by:

$$T_{\mathrm{m}} - T_{\mathrm{amb}} = G / (u_0 + u_1 v) \quad (6)$$

The coefficient u_0 describes the influence of the irradiance and u_1 the wind impact.

NOTE The two coefficients will depend upon the mounting method used for the module.

While modules with glass fronts but various semiconductor materials and back packaging can have distinguishably different u_0 and u_1 values it is acknowledged that the given procedure can have uncertainties on the same order of magnitude as this differentiation. The uncertainty in the given procedure is caused by factors such as mounting configuration, sky temperature, prevailing wind directions, seasonal variation, etc. The values determine are highly site specific and need to be evaluated for different locations. The following test procedure shall be conducted.

The measured temperature varies with the conditions of the measurement (sky temperature, ground temperature, etc.). A correction of up to 5 °C may be applied to adjust for the variable conditions. To apply this, two reference modules are placed next to the device under test (one on either side). The reference modules shall have been characterized for >6 months to derive Nominal Module Operating Temperature (*NMOT*). The two reference modules and the device under test are characterized during the same time period and the average deviation from the 6-month *NMOT* values for the two reference modules is applied to the *NMOT* measurement for the device under test.

8.3 Apparatus

The following apparatus is required.

a) An open rack to support the test module(s) and a pyranometer or PV reference device in the specified manner (see item d) below). The rack shall be designed to minimize heat conduction from the modules and to interfere as little as possible with free radiation of heat from the front and back surfaces of the module.

In the case of modules not designed for open-rack mounting, the test module(s) shall be mounted as recommended by the manufacturer.

b) A resistive load sized such that the module will operate near its maximum power point at STC or an electronic maximum power point tracker (MPPT). The load shall be noted in the test report.

c) Means to mount the module, as recommended by the manufacturer, co-planar with the irradiation monitor.

d) A pyranometer or PV reference device mounted in the plane of the test module(s) and within 0,3 m of the test array, accurate to at least ±5 %.

e) Instrument to measure wind speed up to at least 10 $m \cdot s^{-1}$ and down to 0,25 $m \cdot s^{-1}$ installed approximately 0,7 m above the top of the module(s) and mounted close to the module in a position where it will not shade the module.

f) An ambient temperature sensor, with a time constant equal to or less than that of the module(s), installed in a shaded enclosure with good ventilation near the wind sensor.

g) Cell temperature sensors attached to the back side of the module centered behind four solar cells approximately in the positions shown in Figure 2 for wafer based technologies. Choose similar positions for thin film based modules, allowing for the sensor not to be in the center of the cells. Use an infrared camera to check the module for hot-spots under continuous artificial or natural illumination. Avoid placing temperature sensors behind hot cells.

h) A data acquisition system with temperature measurement accuracy of ±1 °C with a repeatability of ±0,5 °C to record the following parameters within an interval of no more than 5 s:
   – irradiance from the pyranometer or PV reference device,
   – ambient temperature,
   – cell temperatures within the module at the four specified places,
   – wind speed.

8.4 Test module mounting

8.4.1 The test module(s) shall be positioned so that it (they) are tilted at 37,5° ± 2,5°. Note the angle of tilt of the test module in the test report (see Clause 5, item j)).

8.4.2 The bottom of the test module(s) shall be at least 0,6 m above the local horizontal plane or ground level.

8.4.3 To simulate the thermal conditions of modules installed in an array, the test module(s) shall be mounted within a planar surface that extends 0,6 m beyond the module(s) in all directions. Modules of the same design shall be used to fill out the remaining open area of the planar surface. Additionally, there shall be a baffle of 2 module widths or 0,6 m whichever is larger beyond the module(s) in both the east and west directions, that is to both sides of the module when facing it.

8.4.4 There shall be no obstructions to prevent full irradiance of the test module(s) during the period from 4 h before local solar noon to 4 h after local solar noon. The ground surrounding the test module(s) shall not have an abnormally high solar reflectance and shall either be reasonably flat and level or slope away from the test fixture in all directions. Natural surfaces such as grass or dirt are examples of acceptable surfaces.

8.5 Procedure

a) Set up the apparatus with the test module(s) mounted as described in section 8.4. Any hot spot protection devices recommended by the module manufacturer shall be installed before the module is tested.

b) Clean the surface of the modules at least weekly or more frequently if significant soiling occurs.

c) Keep the module at or near its maximum power point, by using the resistive load or MPP tracker (see 8.3 b).

d) On suitable clear, sunny days, record as a function of time the module temperature in the four places shown in Figure 2, the ambient temperature, the irradiance and the wind speed within a time interval of less than 1 s. All data shall be sampled a minimum of every 5 s for the purposes of capturing instantaneous wind speeds outside the interval described in 8.3 e). Compute the average of the 4 temperature sensors for all data sets.

e) Reject all data taken during the following conditions:

   – Irradiance below 400 $W \cdot m^{-2}$.

   – In a 10 min interval after the irradiance varies by more than ±10 % from the maximum value to the minimum value during the preceding 10 min period.

   – In a 10 min interval after and including a deviation of the instantaneous wind speed to below 0,25 $m \cdot s^{-1}$ or gusts larger than +200 % from a 5 min running average.

   – All data when the 5 min running average is less than 1 $m \cdot s^{-1}$ or greater than 8 $m \cdot s^{-1}$. This running average should be calculated after having rejected gusts and low wind speed.

NOTE It is suggested to bin the data first for ten minute intervals and carry out the analysis for each interval based on the difference between minimum and maximum irradiance in this bin. It is easier to reject low light conditions first.

8.6 Evaluation

a) Use the data obtained from averaging the module temperatures to calculate the difference between each of the four temperature sensors and their average. Reject the data of the sensor with the largest difference and recalculate the average T_m of the remaining three temperature data sets.

b) Acceptable data points shall come from at least 10 different days and on each of those days there shall be at least 10 data points both before and after solar noon.

c) Using the 5 min average wind speed, there shall be a range of data points covering at least 4 $m \cdot s^{-1}$.

d) From all acceptable data points, making sure that data points from both before and after solar noon are utilized, calculate the average module-temperature and plot $G/(T_m - T_{amb})$ as a function of the 5 min average wind speed. Use linear regression analysis to determine the slope and intercept (u_1 and u_0) of the model.

e) Report dates of start and end of the exposure and the coefficients u_0 and u_1.

There is potentially a large variation in the values u_0 and u_1 due to location and measurement season, thus it is essential to either quote the uncertainties or apply a seasonal correction.

These are ultimately to be used for the calculation of the annualised energy yield and it would be advisable to check the impact of the coefficients on this rather than just looking at the uncertainty of the parameters alone.

The coefficients are then used as specified in IEC 61215-2 to calculate the nominal module operating temperature (*NMOT)*.

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